CHANGES OF THE SURFACE AREA OF MORSKIE OKO AND WIELKI STAW IN THE TATRA MOUNTAINS

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Abstract: This dissertation has presented the results of measurements regarding the surface area of Morskie Oko and Wielki Staw lakes performed throughout the period of 140-years with the use of various measurement technologies and analyses of cartographic resources. The research has clearly demonstrated that the obtained results are diverse, which could be influenced by various environmental factors and the time difference of surveys conducted at the analysed objects. Wielki Staw is currently the largest lake in the Polish Tatra Mountains. Its surface area in 2021 covered 33.44 ha. Thus, it appeared to be larger than Morskie Oko, the surface area of which is 1.51 ha. It was also concluded that the difference in the size of these two reservoirs might increase over time since Morskie Oko is situated in an environment that undergoes dynamic transformations and, consequently, has an impact on the evolution of this lake. Moreover, the area surrounding Morskie Oko is one of the most popular tourist locations within the Tatra National Park, which may intensify the anthropogenic impact on the course of, among others, the shoreline.

Key words: Morskie Oko, Wielki Staw, mass movements, Tatra Mountains, Tatra National Park

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Introduction

Lake ecosystems are very vulnerable; they undergo multidirectional transformations influenced by the type of the geographical environment they are situated in. In particular, dynamic changes can be observed in the case of mountain lakes. One of the factors that initiate such metamorphoses are mass movements. They are a natural phenomenon which is usually triggered by several factors: predispositions of the landform, geology, tectonics, and suitable weather conditions.

The occurrence of these phenomena intensifies in mountain regions. Rockfalls, snow and debris avalanches are often reported in Alpine ranges. In Poland, such phenomena can be most often observed in the Tatra Mountains (Gądek et al. 2010, 2016, Jurczak et al. 2012, Jodłowski et al. 2021, Rączkowska 2021). They pose a threat to people and can lead to significant environmental changes, with a significant impact on evolution of lakes.

Morskie Oko and Wielki Staw are considered the largest lakes in the Tatra Mountains, and since the first time they were surveyed, they have kept swapping their positions in the statistical priority in the hierarchy of the covered surface area. This situation causes much confusion. Various sources present contradictory data. Thus far, it has been impossible to resolve this problem since

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there have been no measurements that would be taken for both lakes in the same year. On top of that, there is no information on the time per year the said bodies of water were surveyed or on the water level at the time of measurement.

Therefore, the aim of this paper has been to make an attempt of analysing the environmental factors that may have an impact on the transformation of the lakes. Additionally, the aim of this dissertation is to compare surface areas of the lakes based on documentation drawn up at the same time both for Morskie Oko and Wielki Staw, which is crucial in order to obtain objective results.

Resources and methods

It was decided that the survey would cover two lakes located in the High Tatra Mountains, within the Tatra National Park, namely, Morskie Oko and Wielki Staw Polski. Both lakes are pretty close to each other, have similar size, shape and length of the shoreline. Moreover, their difference in elevation a.s.l. is insignificant. It was found, based on the specified properties, that the said reservoirs functioned in more or less analogous environmental conditions.

Furthermore, it was assumed that comparing both lakes should be based on cartographic resources preferably drawn up for the said objects on the same date. Thus, the analysis utilised orthophotomaps drawn up for Morskie Oko and Wielki Staw on 9 September 2021 and 20 August 2009. Morskie Oko is depicted in the M-34-101-A-c-4-1 map sheet, while Wielki Staw Polski within map sheets M-34-101-A-c-1-4 and M-34-101-A-c-3-2. These resources were accessed via websites of the Head Office of Geodesy and Cartography (GUGiK) in Warsaw.

Due to the fact that comparison of shoreline of Morskie Oko in years 2009 and 2021 revealed significant differences in its shape, an additional analysis was included for an aerial photograph 7b_4328 taken in 1964, which encompasses both Morskie Oko and Wielki Staw. Unfortunately, the exact date when the picture was taken is unknown. Specific dates of photographs from other sources were provided by employees of GUGiK in Warsaw. Aerial photographs and orthophotomaps were analysed using GIS software.

Results and debate

When it comes to direction in evolution of their basins, mountain lakes generally differ from their lowland counterparts. The latter are often flow-through and, due to various types of catchment covers, supplied with great amounts of biogenes. This leads to the rapid expansion of coastal vegetation and intensive pace of sedentation and sedimentation of sediments. Moreover, lowland lakes are usually shallow – their average depth in Poland is 7.4 m (Choiński 2007), which most certainly favours the process of decline. Apparently, it seems that mountain lakes are more resilient to drying up. They are often situated at heights characterised by scarce flora or surrounded by solid rock and soil in the area is weakly developed, with a skeletal structure that results in its insignificant water capacity.

It is generally agreed that lakes in high mountains are situated in secluded regions far from human impact. In the example of Morskie Oko, the said claim is just partially correct. After World War II, the region around Morskie Oko was used for intensive sheep farming. Vegetation, including dense mountain pine, started to grow on the bare sections of the catchment only after the establishment of the Tatra National Park. In 1955, dwarf mountain pine in the catchment of Morskie Oko covered 2.4 ha of land; in 1977, it was 7.25 ha, while in 2004, it was 15.01 ha (Pociask-Karteczka et al. 2014). Thus, the area taken by mountain pine increased more than six times within half a century. In the case of Morskie Oko, the changes which occurred on the surface of the catchment could lead to a reduced surface runoff and, consequently, to increased evapotranspiration and interception. Therefore, the lake will be supplied with less water of lower density, which can lead to a different reaction of water levels than several decades ago.

Due to oligotrophic water, life in mountain lakes is extremely scarce. For instance, the shores and the littoral zone have no vegetation. Such lakes, however, are also exposed to processes that may lead to a rapid decline resulting from basins being filled with sediment. This results from:

– extremely high annual rainfall, that is, 2–3 times higher than levels measured in the lowlands. This leads to very intensive surface runoffs, supplying mineral mass along with

the flow, which translates into formation of deltas and deposition of smaller fractions further from the shore;
- snow avalanches along with carried vegetation, such as dwarf mountain pine, moss and lichens, transport various fractions of clastic material to the ice surface;
- mass movements resulting in shifts of slope sediments, fragments of surface rocks and rock mantle accumulated on the slopes. In extreme situations, the largest fractions of rock material masses that fall into water might be deposited in significant distances from the shore, that is, several to a dozen meters, while the finest fractions which were originally suspended can settle at the bottom even farther. Rockfalls, landslides and creeps of the rock material can lead to either shallowing of the littoral zone or shifting of the shoreline towards open water;
- intensive snowmelt, which supply lakes with large amounts of slope material, mainly in fine fractions.

To a great extent, the phenomena described previously refer to mountain lakes. The scale and the pace of phenomena that have impact on the evolution of the lake basis can be exceptionally substantial. It results from the differentiation in the environment surrounding a particular lake, which can determine the pace of shallowing and its final phase, that is, decline.

Lakes, such as Morskie Oko in Dolina Rybiego Potoku and Wielki Staw in Dolina Pięciu Stawów Polskich in the High Tatra Mountains, serve as good examples of lakes which can be subjected to a comparative analysis in terms of basin evolution. Both lakes have two common features, namely, the outlet of Rybi Potok from Morskie Oko and Roztoka from Wielki Staw and a very similar size of surface area. What are the factors, if any, that determine their varied susceptibility to processes that lead to different speed of drying up? Which of the presented lakes is more resistant to the impact of its surroundings, leading to a decrease in the surface area and volume of basins? Answers to these questions can be found by analysing the natural conditions near the lakes.

The first distinctive feature of both lakes is their location with regard to the nearby mountain peaks (ZTSGWP 1984). The water surface of Morskie Oko is at the height of 1395 m a.s.l., and it is surrounded on three sides by peaks >2000 m a.s.l. (Fig. 1), with the highest being Mięguszowiecki Szczyt with 2438 m a.s.l., and it is 950 m in a straight line away from Morskie Oko. The difference in height is then 1043 m. Among other mountain peaks neighbouring Morskie Oko, there are Cubryna, Opalony Wierch, Żabi Szczyt Niżni and Żabia Czuba. When it comes to Wielki Staw situated at a height of 1664 m a.s.l., the difference between its water level and the surrounding peaks is far less significant. Thus, the highest peak near Wielki Staw, to the northwest, is Kozi Wierch (1.1 km from the lake shore), with a height of 2291 m a.s.l. This means that the height difference in this case is only 627 m. In the case of other high peaks, such as Miedziane or Niżni Liptowski Kostur, the differences in height are even lower, that is, of 500–600 m (Fig. 2).

Thus, in the case of Morskie Oko, due to greater differences in height and shorter distances between the lake and the nearby mountain peaks, the slopes are steeper, and the slope processes

Fig. 1. General view at Morskie Oko and its surroundings from south (Choiński 2021).

Fig. 2. General view at Wielki Staw and its surroundings (Choiński 1998).

can be of greater intensity as in the case of areas neighbouring Wielki Staw.

Lakes are situated differently within the area of Pleistocene and Holocene formations. Except for its northern shore, Morskie Oko is surrounded with scree and colluvium with a width of 200–300 m in the area, of which, especially in the south-eastern part, 10 scree channels were formed with lengths of up to several hundred metres. Wielki Staw is largely surrounded by moraine covers, while the four scree channels near the north-western shore are several times shorter than their equivalents near Morskie Oko (Michalik 1985). The situation suggests that the area near Morskie Oko is more susceptible to mass movements on slopes. An example of rockfall is presented in Figure 3, in which one can see the effect of the clastic material transported in the form of a 'cloud' over the slope of Mięguszowiecki Szczyt, where rockfalls move in a gravitational manner, initiating air pollution with the finest fractions forced off the ground. The said rockfall took place on 22 October 2021. In this example, some of the rock matter can be deposited within lower sections of the slope, some may end up in the lake and the finest fractions which are 'suspended' in the air can fall onto the water surface.

Corrasion gullies and channels are also far more common and more developed near Morskie Oko (Klimaszewski 1985). Currently, the most dominant morphogenetic processes in the area of Morskie Oko, except for its northern shore, are flows of debris or mud and debris, suffosion, and avalanche accumulation. In the case of Wielki Staw, on the other hand, the processes around the majority of its shores are suffosion, flushing and avalanche accumulation, while on the south-eastern shore, gravitational accumulation of debris, nivation and suffosion (Kaszowski, Kotarba 1985).

Very significant differences between the surroundings of both lakes manifest themselves with regard to routes of debris flows, both old and new (Figs 4 and 5). According to Kędzia (2017), the 1930s and the 1940s were characterised by an increased activity of debris flows. The next wave of increased frequency of debris flows in the Tatra Mountains, which has lasted until now, started in the 1970s. Figure 4 presents two colluvial deposits in contact with the shoreline along approximately 120 m, which constitutes almost 5% of the lake perimeter. A huge rockfall, the outcome of which is depicted in Figures 4

Fig. 4. General view at the southern shore of Morskie Oko which was reached by the face of rockfalls (Choiński 2016).

Fig. 3. Rockfall from the wall of Mięguszowiecki Szczyt moving towards Morskie Oko on 22 October 2021 (Denega 2021).

Fig. 5. One of the rockfall tongues photographed from a short distance from the water surface. One can clearly see the contact of freshly deposited mantle that penetrated the lake (Choiński 2016).

and 5, took place on 25 July 2016. The debris was removed from the affected trail on 3rd and 4th of August 2016 (oral information, Łukasz Pęksa).

In general, such trails do not reach Wielki Staw, while there is a dozen that leads to the shoreline of Morskie Oko, except for its northern section (Długosz 2015).

The potential avalanche routes are extremely important in terms of their number, range and amount of transported snow mass. Such a situation is presented in Figures 6 and 7, which show the effects of an avalanche that moved from Marchwiczny Żleb onto the ice surface of Morskie Oko on 2 February 2022. The extent of an avalanche can be assessed by paying attention to the remains of dwarf mountain pines protruding from the snow, that is, up to approximately 150 m from the western shore of the lake. The ice cover on the lake was split up in the coastal area.

Fig. 6. Avalanche field on the surface of Morskie Oko which was formed on 2 February 2022 (Denega 2022).

Fig. 7. Fragments of dwarf pine deposited by a snow avalanche on 2 February 2022 on the surface of the cover (Zieliński 2022).

The farther from the shore, the more difficult it is to assess its condition due to the thickness of the avalanche snow layer covering the ice surface. On the date of the avalanche, the said layer of snow was 40 cm thick (oral information, Barbara Staniszewska). Determination of the amount of clastic material brought by the avalanche onto the ice surface is a difficult task. However, if there were uprooted dwarf mountain pines, it can be assumed that the transported mass included the slope rock mantle, which will be deposited at the bottom of the lake after thaw.

Wielki Staw has three such locations of avalanche movement (from the south-eastern side), whereby the potential area of their accumulation covers approximately 20% of the surface of the lake. In the case of Morskie Oko, there is a dozen of avalanche routes, while the potential accumulation area amounts to 85% of the surface of the lake (Žlak, Długosz 2015).

As it has been proven through the comparisons mentioned earlier, Morskie Oko is far more likely to undergo processes connected with the decline of the basin than Wielki Staw.

The basin stability of mountain lakes can be often maintained for many years, both in terms of surface area and their capacity. The disturbance of such a system can occur abruptly and last only for a ‘moment’. This is the characteristic of unpredicted movements of rock masses (especially those larger in scale) that cross the shoreline. Such incidents are, by definition, strictly random.

The outcomes of such phenomena have been documented differently in several works. Piasecki (1958), when analysing Mały Staw in the Karkonosze Mountains and their surroundings, concluded that the bottom of the lake is covered by debris accumulation with thickness of up to 14 m. Choiński (2003), who analysed the bathymetric plans of Mały Staw and Wielki Staw in the Karkonosze Mountains elaborated within a time interval of approximately 50 years, defined the indicators regarding the shallowing of the lakes and their potential age. Similar conclusions with regard to these lakes were presented by Łyczkowska (2003, 2009) who reported that each time, moving snow avalanches supply rock material towards the vicinity of lakes in form of debris covers or it is directly deposited at the bottom of the lake, which causes its shallowing. Borowiak (2000a, 2002) described a spectacular example of changes in the geometry of the basin of Czerwony Staw Gąsienicowy Zachodni. For example, as a result of debris flow caused by high precipitation, the surface area of the lake decreased by almost 15%, changing its capacity by 28%. According to the author, the lake became shallower by 8 cm within several hours, which under normal circumstances of sedimentation for intermoraine lakes can last for >500 years. One of the methods that allow specifying the ongoing changes of lake basins is to compare the bathymetric plans or aerial photographs from various periods. However, the latter constitutes a fairly young type of research material. On the other hand, the first bathymetric plans, for example, that are >100 years old, are extremely rare and of low accuracy. The work of Choiński and Strzelczak (2011) concerning Morskie Oko can be an example of efforts to document it. The said elaboration analysed four depth plans dated 1879, 1909, 1934 and 2011. However, it is impossible to use them as the ground for a clear conclusion on whether the lake evolves towards its decline. Still, the applied measurement methods are not the only factor that can cause the discrepancies between the obtained results and the actual values. The analysed lakes, that is, Morskie Oko and Wielki Staw, can serve as an example, and according to Borowiak (2000b), they are very similar in terms of surface area and water levels. Consequently, both lakes can alternately be considered as the largest.

Table 1 presents the comparison of surface areas of Morskie Oko and Wielki Staw measured using various methods within the period from 1880 to 2021.

There is much more data available for Morskie Oko. This clearly results from the easier access to the lake, especially when it comes to transporting a vessel. It is commonly assumed and proven in majority of elaborations that Morskie Oko is the largest lake in the Tatra Mountains. This statement can be found, among others, in encyclopaedic resources such as Nowa encyklopedia powszechna PWN (1997), Encyklopedia szkolna PWN (2002), Wielka Encyklopedia PWN (2003) and Paryski, Radwańska-Paryska (2004). Can this statement be proven in the light of the most up-to-date data? Even the author of data presented in Table 1 – Śliwerski (1934) – had some doubts, although he claimed that Morskie Oko was larger than Wielki Staw by 0.4 ha. He highlighted that the difference determining the priority of Morskie Oko was not solid enough to ensure ultimate dominance. It resulted from the fact that Morskie Oko was measured from the water surface in spring, during a period of high-water level, while the measurements of Wielki Staw were taken from ice, when the water level was lower. Apart from that, the shoreline of Wielki Staw in its southern parts was designated with small approximation due to accumulated heaps of snow. According to Śliwerski (1934), the lakes in question can exceed one another in size due to their similar surface areas. It depends on their water levels that can change in an asynchronous manner and to a varied degree.

The comparison of the surface areas of Morskie Oko and Wielki Staw in the last years has indicated that Wielki Staw is larger. It could be assumed that the said difference will increase in the future.

Table 1. Surface areas of Morskie Oko and Wielki Staw in the period from 1880 to 2021.

Morskie Oko			Wielki Staw		
Year[1]	Author/source	Area [ha]	Year[1]	Author/source	Area [ha]
1880	E. Dziewulski	30	1880	E. Dziewulski	33
1910	L. Sawicki	33.42	1910	L. Sawicki	35.78
1934	K. Śliwerski	34.54	1934	K. Śliwerski	34.14
1964	Aerial photo 7b_4328	33.07	1964	Aerial photo 7b_4328	34.33
2009	Orthophotomap M-34-101-A-c-4-1	32.95	2009	Orthophotomap M-34-101-A-c-1-4 M-34-101-A-c-3-2	34.44
2011	A. Choiński A. Strzelczak	33.39	–	–	–
2012	J. Urbański et al.	32.62	–	–	–
2021	Orthophotomap M-34-101-A-c-4-1	32.93	2021	Orthophotomap M-34-101-A-c-1-4 M-34-101-A-c-3-2	34.44

[1] Dates of field surveys can vary from the dates on which the results of studies were published.

On the one hand, it results from the morphometric indicators of both lakes. In this matter, those regarding Morskie Oko are far more unfavourable and predisposing for a quick decline than in the case of Wielki Staw. The said indicators are as follows:

- lower maximum depth, that is, 51.8 m and 80.3 m (Choiński 2000),
- lower average depth, that is, 28.4 m and 37.7 m (Szaflarski 1936),
- shorter shoreline, that is, 2484 m and 2580 m (an analysis of orthophotomaps from 2021),
- lower inclinations of the bottom, that is, 15°22' and 19°15' (Radecka 1993),
- water resources lower by 20.4%, that is, 9,935,000 m^3 and 12,967,000 m^3 (Szaflarski 1936),
- higher percentage of coastal zone with a depth up to 5 m (calculated with the use of planimetry between the shore and the 5-m isobathic line according to bathymetric plans by Sawicki dated 1929), that is, 6.0 ha and 4.55 ha. Thus, Morskie Oko has a larger area susceptible to drying up.

On the other hand, the factors that have an influence on the faster decline of Morskie Oko include the already mentioned conditions found in catchments of both lakes:

- greater differences in relative heights in the catchment,
- greater inclinations of rock slopes in the catchment,
- better formation of gullies and corrosive channels in the direct vicinity of Morskie Oko,
- more avalanche ducts with a far wider area of impact.

Moreover, the closest surroundings of Morskie Oko are characterised by much higher anthropopressure. It has a multidirectional impact. On some occasions, it results in transporting mineral material due to the pressure caused by the weight of human body against the ground. Hikers who are on their way towards the shoreline may initiate the movement of even small pebbles. Unfortunately, people also throw various items into the lake, such as coins and stones. Sometimes, they also wash their hands and face or immerse their feet in the water. Morskie Oko is one of the most popular places in the Tatra National Park. On summer days, the region in question can be visited by >10,000 people (Król 2022). Excessive anthropopressure may lead to severe ecological issues. To visualise this problem, one can simply assume that each visitor will take one so-called sanitary break.

It is difficult to assess the pace at which the surface area of both analysed lakes will be reduced. Contrary to lowland lakes, which are characterised by a stable annual course of sedimentation and sedentation, mountain lakes are

Fig. 8. Changes in the course of the shoreline in the southern part of Morskie Oko. Source: orthophotomap from the resources of GUGiK.

dominated by unpredictable mass movements, which constitute the main factor affecting the evolution of the basins. Figure 8 is a perfect example. It presents the changes in the shoreline of the southern section of Morskie Oko. It covers the course of the shoreline in 1964 and in 2021 based on an orthophotomap dated 2009. One can notice distinct differences that are reflected in the data presented in Table 1 for Morskie Oko and its measurements performed in 1964, 2009 and 2021. It appears that the surface area of Morskie Oko decreased by 12 acres within the period from 1964 to 2009 and only by 2 acres in the period from 2009 to 2021. According to Choiński and Strzelczak (2011), Morskie Oko had an inconsiderably larger surface area, while Urbański (2014) claimed that the surface area was smaller than the results obtained based on analyses of orthophotomaps dated 2009 and 2021 (Table 1). At the same time, it should be highlighted that both the surface area and the course of the shoreline of Wielki Staw were the same in years 2009 and 2021. No differences in the course of the shoreline of the lake have been identified since 1964, despite the fact that the surface area in 1964 was 11 acres smaller than that in years 2009 and 2021. Most probably, the smaller surface area can be attributed to water-level fluctuations.

Fig. 9. An example of a northern part of the shore of Morskie Oko that is composed of boulders with relatively vertical walls; thus, water-level fluctuations do not influence the changes in surface area (Choiński 2016).

Fig. 10. An example of a section of shoreline, determination of which is difficult. It results from the fact that it is dispersed by boulders which form very small islands. The water surface between them is so diverse, and it forms an obstacle in finding the 'solid ground' (Choiński 2016).

When it comes to the dynamics of water levels, both examined lakes show similarities. In the case of Wielki Staw, the only available data cover the period of 1968–1979. Thus, data regarding Morskie Oko in the same period were used for comparative purposes. The noted amplitudes of extreme levels were, respectively, 89 cm and 108 cm. The maximum annual levels and annual amplitudes determined for both lakes were characterised by a decreasing trend, while the average and minimum levels remained stable (Choiński 2016). In the case of the last quoted years, it results from the relatively constant erosion bases of the outflow from both lakes, which do not 'allow' for outflows of waters below the 'threshold' ordinates. Moreover, changes in the surface areas of water bodies do not necessarily reflect the water-level fluctuations (Fig. 9). Furthermore, proper designation of the shoreline is often quite problematic (Fig. 10).

Conclusions

The analysis of primary sources and cartographic materials revealed a certain discrepancy in the measurements taken for the surface area both in the case of Morskie Oko and Wielki Staw. The said differences can arise from natural and anthropogenic changes in the environment within the analysed time frame of 140 years. Most certainly, the said differences result from the varied methods of field measurements and using measurement equipment and cartographic materials of different accuracy. The specific nature of shoreline of the lakes in question, which has posed many measurement and interpretation difficulties until now, is of great importance as well. Nevertheless, it can be clearly stated that

Wielki Staw has the largest surface area of all the lakes in the High Tatra Mountains. Its determined surface area, based on orthophotomaps of 9 September 2021, is 34.44 ha. The surface area of Morskie Oko, measured based on an orthophotomap of the same date, was 32.93 ha. Thus, Morskie Oko is smaller by 1.52 ha. The vast and often few hundred metres high rock walls surrounding Morskie Oko transport much more debris than their lower counterparts around Wielki Staw. Additionally, 85% of the surface of the basin of Morskie Oko is endangered. This is several times higher than that of the basin of Wielki Staw. Apart from that, Morskie Oko is characterised by more frequent hazards from a higher number of directions. The southern part of the lake is especially exposed to debris flows, which consequently may lead to shifting of the shoreline of the reservoir towards north, making that part of the reservoir shallower. The western stretch of Morskie Oko accumulates snow masses transported due to avalanches. It should be expected that the degradation of Morskie Oko will be more intensive and dynamic than that of Wielki Staw. Thus, it is most probable that the disproportion between the surface areas of those lakes will increase. Moreover, Morskie Oko will still be subjected to far more concentrated anthropopressure, which affects the stability of lake shorelines and ecosystems.

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Author's contribution

ACh is the originator of the work. The authors jointly created the study and made corrections to the earlier text to an equal extent.

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