

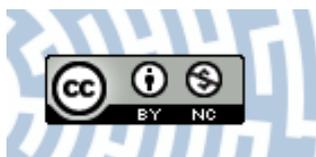


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Classification of the Tatra Mountain lakes in terms of the duration of their ice cover (Poland and Slovakia)

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ABSTRACT

This paper presents the results of a classification of the Tatra lakes based on the duration of their ice cover, altitude, volume, and potential incoming solar radiation (PISR). It is embedded in the context of the impact of current climate change on the mountain environment. A digital elevation model, morphometric data, satellite imagery from the winter seasons of 2015-2017 and the Wrocław taxonomy method were used in the study. It was found that the order of freezing and thawing of the lakes investigated may change from year to year. The relationship between ice cover duration and altitude is clearly weakened by variations in lake volumes, with insolation having a noticeably lesser effect. Determining the duration of ice cover of the lakes over several seasons facilitates identifying the similarities and dissimilarities between them. Five groups of lakes displaying similar characteristics were identified as well as 2 groups of lakes with highly individual characteristics. Based on the data obtained, it can be concluded that the duration of ice cover on the Tatra lakes has been shortening noticeably over the last 100 years. Small high-altitude lakes seem to be most vulnerable to climate change.

INTRODUCTION

The ice cover of lakes is one of the seasonal components of the cryosphere (Barry and Gun, 2011), and its long-term variability may reflect changes in the Earth's climate (Sharma *et al.*, 2016). By stopping the mixing of water by wind and changing the light conditions and exchange of heat between the water and the atmosphere, the ice cover influences the physical, chemical and biological processes that shape the lake ecosystem (Mishra *et al.*, 2011; Leppäranta, 2010; Krillin *et al.*, 2012; Hampton, 2017; Wang *et al.*, 2018).

Present-day climatic warming (IPCC, 2013) leads to a decrease in the maximum thickness of the ice cover of

lakes and to a shortening of its duration. As has been observed, there is a growing tendency for lakes of the Northern Hemisphere to freeze later and thaw earlier, which is related to the shortening of thermal winters (Palecki and Barry, 1985; Magnuson *et al.*, 2000; Hodgkins *et al.*, 2002; Williams *et al.*, 2004; Brown and Duguay, 2010; Benson *et al.*, 2012; Apsite *et al.*, 2014; Kainz, 2017; Sharma *et al.*, 2019). However, lakes may differ significantly in terms of the pace of changes and the duration of the ice cover (Assel *et al.*, 2003; Marszelewski and Skowron, 2006; Weyhenmeyer *et al.*, 2011; Nöges and Nöges, 2014). In addition to local circumstances, the teleconnection conditions may be of great importance (Livingstone, 1997; Choiński *et al.*, 2015a; Van Cleave *et al.*, 2014; Ptak *et al.*, 2019).

The key topographic and morphological determinants of the duration of lake ice cover include, among others, the altitude, surface area, depth and shading of lakes (Šporka *et al.*, 2006; Novikmec *et al.*, 2013). The freezing is largely determined by weather and by internal factors (the lake's surface area and depth), while the thawing depends in the first place on atmospheric conditions (Krillin *et al.*, 2012). For this reason, the ice cover duration differs greatly both in terms of time and space, with many mountain lakes characterised by the "individualism" of ice-related phenomena.

The most widely accepted thermal taxonomy of lakes refers to water mass mixing regimes (Hutchinson and Löffler, 1956; Lewis, 1983; Woolway and Merchant, 2019). However, lakes of the same type in terms of the mixing regime may differ in heat resources, the ice cover duration and sensitivity to climate change, which is attributable to the heterogeneity of lake sizes and properties of the natural environment (Skowron, 2009). In the Tatras, the lakes were divided into classes based on the maximum temperature of surface waters in the

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summer and the duration of the seasonal ice cover in the first half of the 20th century (Lityński, 1917; Szaflarski, 1936). In recent decades, the duration of the ice cover has been found to have been shrinking (Pociask-Karteczka and Choiński, 2012; Choiński *et al.*, 2015b). Gądek and Szypuła (2015) presented the duration of ice cover on the Tatra lakes in the years 1999–2010 on a 1:250,000 scale map. However, their study is characterised by a low temporal and spatial resolution. Both international and local literature lacks complete and up-to-date data on the variations in the ice cover of lakes and the underlying causes across an entire mountain region.

This paper has prepared a classification of the Tatra lakes combining the duration of their ice cover, altitude, size and shading, which will be useful in geoecological research on the effects of present-day climate change. It also demonstrates how publicly available data can be used to group lakes of any mountain region for typology purposes, *e.g.* for the needs of detailed reference research and comparisons. In this study, use is made of the digital elevation model (DEM) of the Tatra Mountains, the Solar Radiation module of the Arc GIS software (ESRI, 2017), morphometric data concerning the lakes of the region, satellite imagery from the winter seasons of 2015–2017, and the Wrocław taxonomy method. The cluster analysis method employed allows the lakes to be grouped objectively with no need to first assume the number of classes. In addition, the boundaries between the classes distinguished are measurable and the structure of the similarities between the objects researched is conspicuous (Senetra and Szarek-Iwaniuk, 2019).

Regional settings

The Tatras are the highest mountain range in the Carpathians (Gerlach: 2655 m asl). They are located in central Europe between the Alps, the Scandinavian Mountains and the Caucasus (Fig. 1). The Tatras cover an

area of about 790 km² (Balon *et al.*, 2015), about 22% of which lies in Poland, and the rest in Slovakia.

In the Pleistocene, this area was repeatedly glaciated (Lindner *et al.*, 2003). At the time of maximum spread of the Würmian glaciers, the equilibrium line altitude (ELA) was probably close to 1500 m asl (Zasadni and Kłapyta, 2014; Engel *et al.*, 2017; Makos *et al.*, 2018). Currently, the upper tree line runs at this altitude, while the present-day climatic snow line (CSL \approx ELA) runs over 1000 m higher (Zasadni and Kłapyta, 2009). The present-day orographic snow line on the northern side of the Tatra Mountains is marked by the lowest-lying firn-ice patches (nourished by snow avalanches), which has ranged between 1530–1980 m asl over recent decades (Gądek and Szypuła, 2015). Above the upper tree line, the environment has periglacial features (Rączkowska, 2007; Lajczak *et al.*, 2014).

The present-day climate of the Tatras is transitional between maritime and continental influences. The mean annual air temperature (MAAT) in the northern and southern forelands (around 850 m asl) is approximately 6°C and 8°C respectively. On the highest peaks, MAAT is < -2°C (Łupikasza and Szypuła, 2019). In the second half of the 20th century and in the first decade of the 21st century, the Tatras recorded an increase in air temperature in winter and summer, as well as a decrease in the total annual snowfall (Żmudzka, 2011; Gądek, 2014). This process has been accompanied by a decrease in the maximum thickness and duration of the snow cover (Falarz, 2002) and the ice cover of lakes (Pociask-Karteczka and Choiński, 2012).

There are 262 lakes in the Tatras (Kopáček *et al.*, 2004), all of which are of post-glacial origin (tarn and moraine-dammed lakes). Most of them are situated above the altitude of 1800 m asl. In the central part of the High Tatras, which is built of granitoids, there are 116 large and 105 small lakes (seasonal lakes or lakes <0.01 ha), whereas in the Western Tatras, which are built of crystalline rocks,

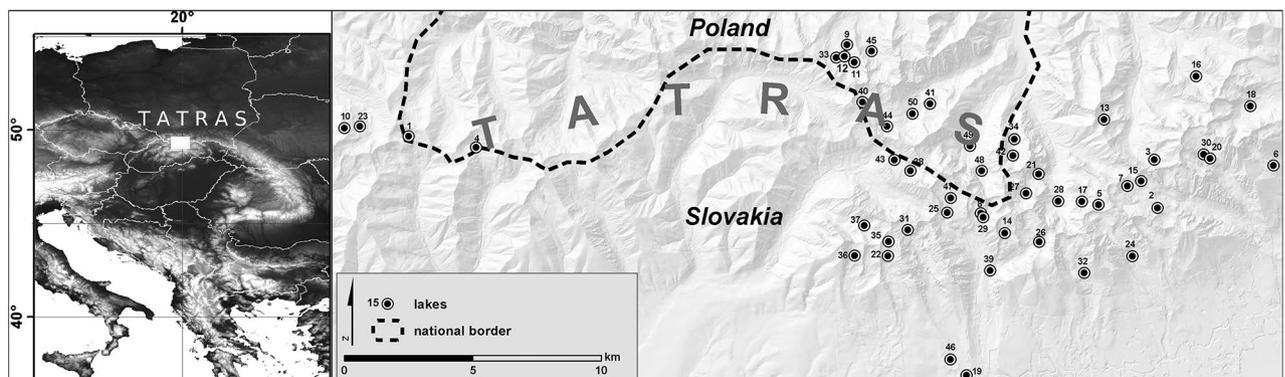


Fig. 1. Location of the study area.

there are 22 large and 18 small lakes. Most lakes are smaller than 1 ha and up to 2 m deep. A majority of them are located on the south side of the Tatra Mountains. The largest lakes, Morskie Oko and Wielki Staw Polski, are on the northern side. The surface area of both exceeds 30 ha, and their maximum depths are 51 and 80 m respectively. The Tatra lakes are usually covered with ice for from 6 to 10 months. In the past, some lakes located at altitudes of more than 2000 m asl could have an ice cover throughout the year (Pacl and Wit-Jóźwikowa, 1974).

DATA AND METHODS

The classification of the Tatra lakes was prepared by means of the Wrocław taxonomy method on the basis of six features: altitude, volume, potential incoming solar radiation (PISR), and the number of days with ice cover in three subsequent seasons (Tab. 1). In this way, account was taken of both external and internal conditions as well as temporal variability in the duration of ice cover, and more significance was given to the latter in the analytical procedure adopted. All features were checked using basic statistical methods.

Data acquisition

In the study, use was made of a digital elevation model (DEM) of the Tatras with a resolution of 10x10 m and the vector layer of lakes (shapefile) of the digital map of the hydrographic division of Poland, which also includes the Slovak part of the Tatra Mountains (IMGW, 2007). Based on these, a set of lakes with an area of >1.0 ha was identified, the altitudes of these lakes were determined, and the values of annual total potential incoming solar radiation, the amount of solar energy expressed in Watt-hours per square metre that could reach the areas from each sky direction in a given time (Fu and Rich, 2002), were calculated. The calculations were performed in ArcGIS v. 10.5 using the Solar Radiation tool (ESRI, 2017). Data on the volume of individual lake basins were taken from a study by Gregor and Pacl (2005).

The durations of the ice cover of the individual lakes in the 2014/2015, 2015/2016 and 2016/2017 seasons were determined on the basis of the analysis of the results of 95 Sentinel-2 satellite images and 101 Landsat-8 images from October-June. The compositions of True/Natural colour and NDWI spectral channels with the resolutions of 20 m (Sentinel-2) and 30 m (Landsat) used in this paper are available at: <https://apps.sentinel-hub.com>. On their basis, the condition of the continuous ice cover was visually assessed on each lake separately. In order to validate the results of the satellite imagery interpretation, use was made of footage from webcams trained on the following lakes: Morskie Oko, Przedni Staw Polski,

Wielki Staw Polski, Zielony Staw Gąsienicowy, Kurtkowiec, Štrbské pleso, Popradské pleso, Velické pleso, and Skalnaté pleso (<https://www.panorama.sk/sk/webkamery/vysoke-tatry/353>).

Basic statistics

The features analysed were examined by checking their distribution (histogram), setting the maximum and minimum values, as well as by calculating the arithmetic means, standard deviations, and coefficients of variation. The interdependence of the features was identified on the basis of the values of Pearson's correlation coefficient together with verification of their statistical significance by means of the *t*-test.

Wrocław taxonomy

This method consists of the grouping of multi-feature objects into internally homogenous classes, but which are and heterogeneous between each other. Objects, which are characterised by standardised quantitative features, create a cloud of points of an *n*-dimensional (number of features) space (Florek *et al.*, 1951). The similarity/dissimilarity of objects is measured by the average difference in their features which is referred to as the taxonomic distance (D_{ij}):

$$D_{ij} = \sum_{k=1}^n \left| \frac{x_{ik} - x_{jk}}{n} \right| \quad (\text{eq. 1})$$

where:

D_{ij} - taxonomic distance between objects (lakes) *i* and *j* for $i \neq j = 1, 2, \dots, m$, *m* - number of objects, x_{ik} - standardised value of the *k*-feature for the *i*-object for $k = 1, 2, \dots, n$, x_{jk} - standardised value of the *k*-feature for the *j*-object, *n* - number of features.

The smaller the taxonomic distance, the greater the similarity between the objects being compared in terms of the features in question. The division of objects into classes can be made on the basis of the critical distance. In order to determine its value, all the Hellwig (1968) criteria were used. However, the best result was achieved with the assumption that the critical distance is equal to the arithmetic mean of the smallest taxonomic distances between lakes.

The basis for the classification of the Tatra lakes was a matrix composed of 50 columns (number of lakes) and 6 rows (number of features). The taxonomic distances between the individual lakes calculated with the use of equation (1) and their classes distinguished on the basis of the critical distance are presented in the form of a dendrite (Fig. 2). The core of each class consists of the two objects (lakes) lying closest to each other within the space of features (the smallest taxonomic distance). The taxonomic distances of the other objects of a given class from its core do not exceed the critical distance.

Tab. 1. List and characteristics of Tatra lakes with an area of >1 ha.

No.	Lake name	Area (ha)	Altitude (m asl)	Volume (m ³)	PISR (Wh/m ² /a)	No. of days with a lake ice cover in the season 2014/2015	No. of days with a lake ice cover in the season 2015/2016	No. of days with a lake ice cover in the season 2016/2017
1	Nižné Jamnicke pleso	1.1	1732	25180	1075099,686	169	177	161
2	Dlhé pleso	1.1	1894	24270	960999,8205	201	180	200
3	Žabie Javorové pleso	1.2	1878	60453	854326,5965	186	194	202
4	Vyšné Račkové pleso	1.2	1697	5624	1043923,686	169	177	160
5	Zamrznuté pleso	1.2	2040	43388	938159,4665	217	209	235
6	Skalnaté pleso	1.2	1751	15874	1162806,843	161	175	177
7	Pusté plesá	1.2	2056	32079	1103229,212	186	193	199
8	Malé Žabie pleso Mengusovské	1.2	1920	45696	1103909,838	186	197	190
9	Dwoisty Staw Wschodni	1.3	1657	48100	1103672,174	175	167	162
10	Horné Roháčske pleso	1.4	1719	46067	1002228,743	169	167	173
11	Długi Staw Gąsienicowy	1.5	1784	81060	1008949,999	178	177	233
12	Kurtkowiec	1.6	1686	34560	1083968,218	175	168	163
13	Zelené Javorové pleso	1.5	1815	17190	810268,6638	176	180	169
14	Dračie pleso	1.7	2020	102835	1045336,741	192	197	187
15	L'adové pleso Zbojnickie	1.7	2057	101133	1160836,88	199	199	211
16	Kolové pleso	1.8	1565	10846	939493,3292	157	161	184
17	Litvorové pleso	1.9	1860	135000	930761,8864	179	211	220
18	Zelené pleso Kežmarské	1.9	1546	31755	927035,919	157	157	184
19	Nové Štrbské pleso	1.9	1312	40640	1119155,941	127	129	137
20	Prostredné Spišské pleso	1.9	2010	50193	1141339,327	175	199	202
21	Ťažké pleso	2.0	1612	47722	1021253,97	162	167	161
22	Nižné Wahlenbergovo pleso	2.0	2053	69701	1093719,909	192	200	222
23	Veľké Roháčske pleso	2.2	1562	77063	997339,884	176	161	157
24	Velické pleso	2.2	1666	45575	1015454,146	159	139	157
25	Malé Hincovo pleso	2.2	1921	72360	1119794,053	169	180	167
26	Ladové pleso v Zlomiskách	2.3	1925	87397	986959,6122	192	197	187
27	Zmrzlé pleso	2.3	1762	86269	794669,716	192	224	183
28	Zelené pleso Kačacie	2.5	1575	28236	865974,7195	155	160	158
29	Veľké Žabie pleso Mengusovské	2.7	1921	73295	1046814,331	185	197	188
30	Veľké Spišské pleso	2.8	2013	124591	1083257,689	179	197	202
31	Capie pleso	3.2	2075	163987	399647,2955	169	190	170
32	Batizovské pleso	3.5	1884	232089	1148697,566	169	169	168
33	Zielony Staw Gąsienicowy	3.8	1672	260500	1011723,232	168	168	170
34	Nižné Bielovodské Žabie pleso	4.8	1675	325244	1000490,533	176	168	164
35	Vyšné Wahlenbergovo pleso	5.1	2157	392078	1089790,039	194	193	200
36	Krivánske Želené pleso	5.2	2013	288685	1047439,035	185	184	190
37	Nižné Terianske pleso	5.4	1940	871668	1037330,363	169	184	170
38	Vyšné Temnosmrečinské pleso	6.0	1725	414712	897689,141	175	179	168
39	Popradské pleso	7.0	1494	504380	1022673,706	155	136	157
40	Zadni Staw Polski	7.1	1890	918400	1090155,878	173	156	174
41	Przedni Staw Polski	7.8	1668	1130000	1072084,045	161	155	160
42	Vyšné Bielovodské Žabie pleso	9.9	1699	839413	871020,5667	169	144	174
43	Nižné Temnosmrečinské pleso	12.1	1677	1501500	1032904,022	172	178	160
44	Czarny Staw Polski	12.7	1772	2825800	1025477,074	165	155	174
45	Czarny Staw Gąsienicowy	17.9	1620	3798000	964082,7048	156	155	160
46	Štrbské pleso	19.3	1347	1299400	1130067,997	131	122	138
47	Veľké Hincovo pleso	20.0	1945	4091712	1095253,329	156	169	173
48	Czarny Staw pod Rysami	20.6	1580	7761700	774008,8202	153	157	160
49	Morskie Oko	33.0	1393	9904300	929704,6406	151	155	157
50	Wielki Staw Polski	34.5	1665	12967000	1074624,602	153	152	153

In order to identify the main features of the lakes in the various classes, the structure of each class was analysed using the method of arithmetic means (Runge, 2007):

$$I = \frac{x_{ck}}{x_{mk}} \tag{eq. 2}$$

where: I - feature significance index, x_{ck} - arithmetic mean of the k -feature of all objects in the class, x_{mk} - arithmetic mean of the k -feature of all the objects in the matrix.

The values of the quotient $I > 1$ indicate the main features that form the classes that are distinguished.

RESULTS

Out of the 262 Tatra lakes, 50 have a surface area of >1 ha. The duration of their ice cover in 2014-2017 and its relationship with altitude, volume and PISR are shown in Figs. 3 and 4, respectively. Meanwhile the results of the classification of these lakes are shown in Fig. 2.

Ice cover duration vs altitude, volume, and PISR of lakes

The average number of days with ice cover for the lakes under study was 174. The shortest duration of ice cover was recorded in the season 2014/2015 (172 days on

average), while the longest was in the 2016/2017 season (177 days). The average standard deviation of this feature was 20 days, and the coefficient of variation was 11.65%. Lakes located at the lowest altitudes, Štrbské pleso (No. 46) and Nové Štrbské pleso (No. 19), were the shortest covered by ice - from 122 to 137 days. Whereas the small and high-altitude Zamrznuté pleso lake (No. 5) was longest covered by ice - from 217 to 235 days) (Tab. 1). In addition to the number of days with ice cover, the ranks of the individual lakes in the list compiled on the basis of this feature also changed from year to year (Fig. 3). However, the correlation coefficient for ice cover on the lakes in the individual seasons was statistically significant, ranging from 0.74 to 0.83.

The duration of ice cover in the seasons analysed was primarily correlated with lake altitude (Fig. 4A). In each case, the values of the correlation coefficients were greater than 0.7. The relationship between the number of days with ice cover and altitude is weakened the most by lake volume (Fig. 4B). It shows a very large spatial diversity. The coefficient of variation of this feature exceeds 244%, but its distribution is not normal, and the standard deviation is more than twice as high as the mean value and amounts to 2,554,714 m³. The correlation coefficient of the number of days with ice cover and the volume of lakes ranged from -0.3 to -0.38. However, no relationship

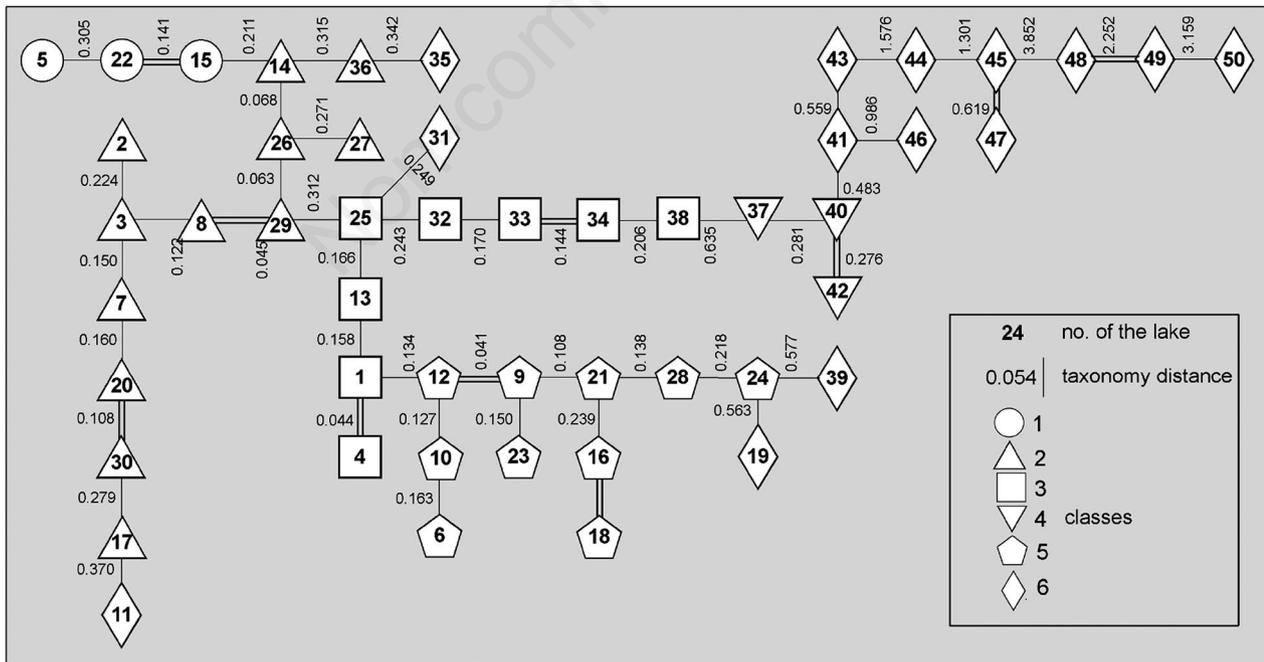


Fig. 2. Results of the classification of the Tatra lakes using the Wrocław taxonomy method (dendrite). Numbers 1-6: lake classes (description in main text); numbering of lakes consistent with their list in Tab. 1; double lines connect the numbers of the lakes which are most similar to each other within the individual classes (cores of the classes); numerical description of the line: taxonomic distance calculated using Equation 1.

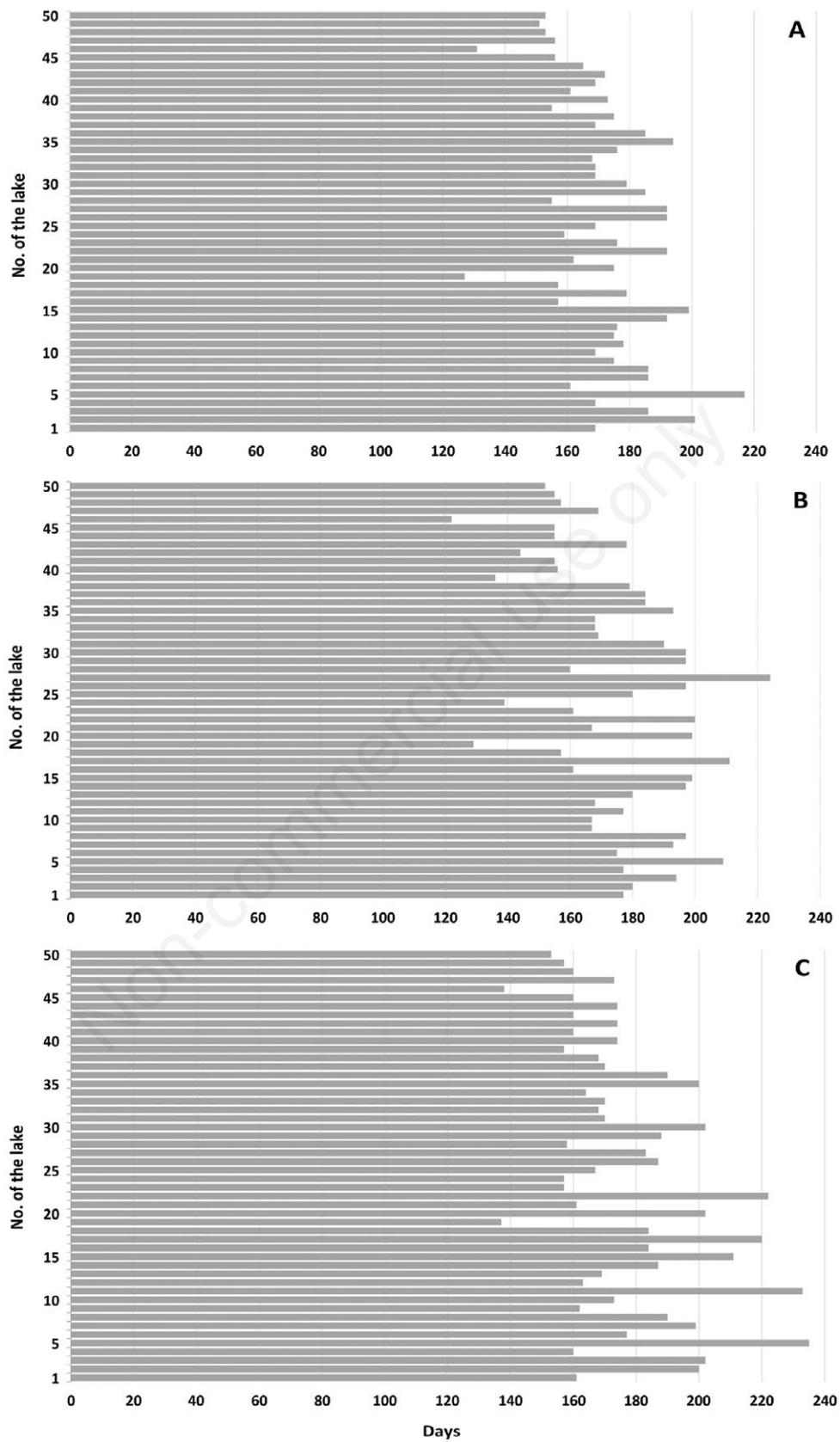


Fig. 3. Duration of the ice cover on the Tatra lakes in the seasons 2014/2015 (A), 2015/2016 (B) and 2016/2017 (C). The numbering of the lakes corresponds with that in the list in Tab. 1.

was found between the duration of ice cover of the lakes and their annual PISR (Fig. 4C). The values of the correlation coefficients of these features in each of the 3 seasons analysed were close to 0.

Classification of lakes

In terms of the features analysed, the lakes Niżné Wahlenbergovo pleso (No.22) and Wielki Staw Polski (No. 50) display the greatest differences, while Dwoisty Staw Wschodni (No. 9) and Kurtkowiec (No. 12) show the greatest similarities. The taxonomic distances between them are 13.54 and 0.04 respectively. The calculated critical distance is 0.43. On that basis, five classes of lakes were identified and 14 lakes are not similar either to one another or to the lakes assigned to classes 1 to 5 (Fig. 2). The topographical and morphometric differences between the individual groups of lakes (both the classified and unclassified ones) are reflected by the duration of the ice cover.

Class 1

The group consists of 3 lakes with a small area (≤ 2 ha). Their average volume is $71,407 \text{ m}^3$. They are situated in the upper, shaded parts of the valleys, at altitudes ranging between 2040 and 2057 m asl. Against the background of all the lakes that were investigated, this group is distinguished by the smallest average potential solar radiation and the longest duration of ice cover. The average value of potential total solar radiation is $80,572 \text{ Wh/m}^2/\text{a}$, while the average number of days with ice cover over the years 2014-2017 was 209.

Class 2

The core of this class is formed by the Malé Žabie pleso (No. 8) and Veľké Žabie pleso (No. 29) lakes. A total of 10 other lakes display significant similarity to these two lakes in terms of the features being studied. All of them are located at altitudes ranging from 1762 m asl to 2056 m asl - mostly on the southern side of the main ridge of the Tatras. They are small and medium-sized lakes. Their areas range from 1.1 ha to 5.2 ha, and the volume from $24,270 \text{ m}^3$ to $288,685 \text{ m}^3$. The potential insolation ranges from $33,304 \text{ Wh/m}^2/\text{a}$ to $94,172 \text{ Wh/m}^2/\text{a}$. The lakes in this class are characterised by a long duration of ice cover. However, in the 3 subsequent study seasons, it was 16 days shorter on average than the duration of the ice cover on class 1 lakes. It fluctuated from 203 to 220 days, with the strongest relationship being demonstrated with the altitude of the lake.

Class 3

The 8 lakes which form this class are situated at altitudes from 1672 m asl to 1921 m asl on both sides of the main ridge. The lakes differ greatly from one another

in terms of size. Their area ranges from 1.1 ha to 6 ha, and volume from 5624 to $414,712 \text{ m}^3$. The core of this class is formed by the lakes Zielony Staw Gąsienicowy (No.33) and Niżné Bielovodske Žabie pleso (No. 34). The whole group is distinguished by the highest insolation and a very homogeneous duration of ice cover. The average monthly

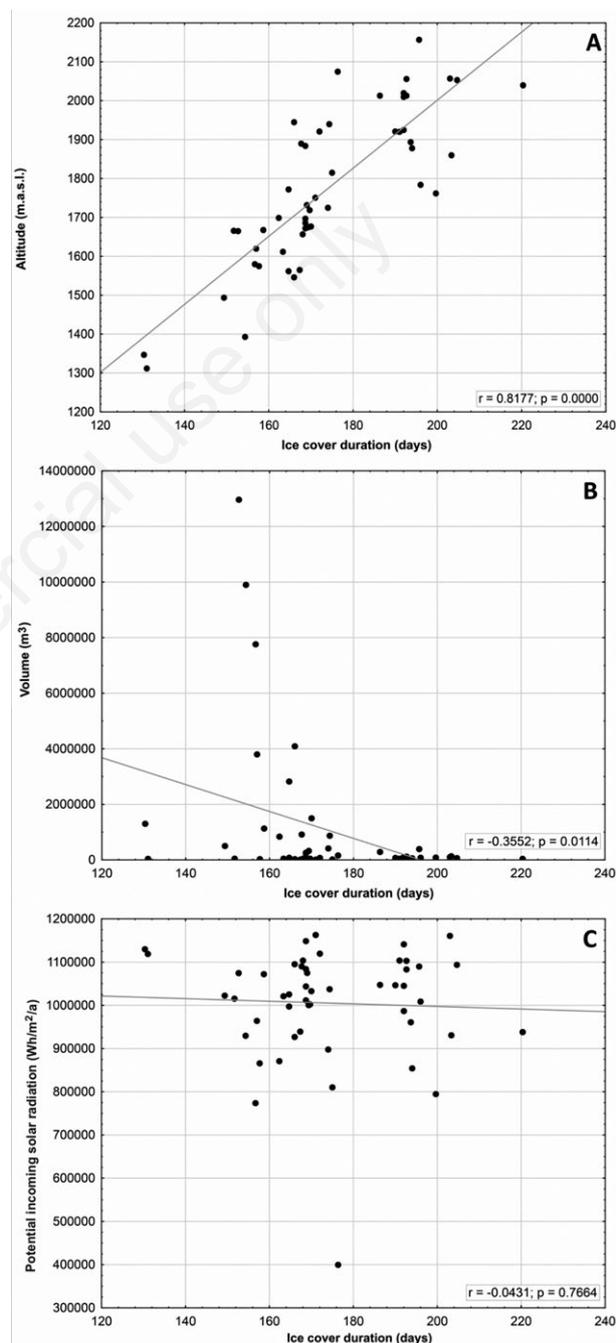


Fig. 4. Relationship between the duration of the ice cover on the Tatra lakes and their altitude (A), volume (B) and potential insolation (C). *r*, correlation coefficient; *p*, statistical significance.

solar radiation is 88,918 Wh/m²/a. In the years 2014-2017, the average number of days with ice cover varied on individual lakes from 169 to 175 and was 22 days shorter on average than on class 2 lakes.

Class 4

This class consists of only 3 lakes. They are located at altitudes between 1670-1940 m asl, and their potential solar radiation ranges from 71,194 Wh/m²/a to 87,235 Wh/m²/a. The average duration of the ice cover fluctuated between 162 and 174 days. In terms of these features, they are similar to class 3 lakes, although they are much larger. Their area ranges from 5.4 ha to 9.9 ha, and the volume from 839,413 to 918,400 m³. In this group of lakes, ice cover duration shows the strongest relationship with altitude.

Class 5

The core of this class, which consists of 10 items, is represented by Dwoisty Staw Wschodni (No. 9) and Kurtkowiec (No. 12). All the lakes are located at relatively low altitude and are small and shallow. They are situated at altitudes from 1546 m to 1751 m asl, their areas range from 1.2 ha to 2.5 ha, and volume from 10,846 m³ to 77,063 m³. The average duration of ice cover of the lakes of this class varied from 152 to 171 days. Their main feature is the relatively high average monthly potential insolation, which ranges from 77,475 Wh/m²/a to 95,112 Wh/m²/a.

Unclassified lakes

Lakes which are not assigned to any of the classes 1-5 on account of their excessively large taxonomic distance do not form separate classes, but instead represent 14 single-item sets. They are present across a large zone of altitudes ranging from 1311 to 2157 m asl and are very varied in size. Their area ranges from 1.5 ha to 34.5 ha, and the volume from 40,640 to 12,967,000 m³. The average potential solar exposure was 81,684 Wh/m²/a, and the duration of ice cover ranged from 130 to 196 days. This group includes all lakes with a surface area >10 ha (43-50). Thus, the predominant feature of the unclassified lakes is their large volume, which means that the duration of their ice cover is shorter. Among the smaller lakes, Długi Staw Gąsienicowy (No. 11) and Vyšné Wahlenbergovo pleso (No. 35) are most similar to class 2 lakes, Nove Štrbské (No. 19) and Popradské pleso (No. 39) to class 5 lakes, and Capie pleso (No. 31) and Przedni Staw Polski (No. 41) to class 3 and 4 lakes.

DISCUSSION

The Wrocław taxonomy is one of the oldest and most widely used hierarchical clustering methods (Pedich,

1977; Mercik, Kołodziejczyk; 1986, Senetra and Szarek-Iwaniuk, 2019). Its results are greatly influenced by the selection of the features of the objects which are compared and the critical distance used. The features on the basis of which objects are grouped should not be strongly correlated with one another (Wierzchoń and Kłopotek, 2018). Of the 6 features used three, *i.e.* altitude, volume, and potential insolation (the latter mainly depending on shading at the spatial and temporal scales used) are not interrelated at all (Tab. 1) and well characterise the topographic and morphometric conditions of the spatial variability of the duration of the ice cover on the lakes. Meanwhile, even though related to the above features, the duration of the ice cover (Novikmec *et al.*, 2013) depends primarily on the weather conditions, which change over time. Thus, this changes from year to year. The order of the lakes ranked in terms of this feature may also change (Tab. 1). Compared to the volume of the Tatra lakes, the duration of ice cover, altitude and PISR have relatively small variability and thus have a less pronounced effect on the differences between the objects studied. However, given that the classification includes the number of days with ice cover from 3 successive seasons, the resultant division of lakes is logical and warranted when seen in the context of natural processes and considerations.

Given the results of the present classification of lakes and the strong relationship between their thermal characteristics and the duration of ice cover with altitude, and thus with the altitudinal zonation of the climate and vegetation (Mirek and Piękoś-Mirkowa, 1992), we propose that the Tatra lakes (with an area of >1 ha) be divided into 7 groups:

- (1) small and shaded lakes of the alpine and subnival zones;
- (2) small and medium-sized lakes in the upper subalpine and alpine and subnival zones,
- (3) small and medium-sized, insolated lakes situated in the upper part of the subalpine zone and in the lower part of the alpine zone;
- (4) medium-large, insolated lakes situated in the upper section of the subalpine zone and in the lower section of the alpine zone;
- (5) small lakes in the area of the upper tree line and in the lower part of the subalpine zone;
- (6) lakes not similar to each other, but showing some similarity to lakes from groups 2-5,
- (7) large lakes (>10 ha) not similar to each other and to lakes from other groups.

The distribution of the thus grouped lakes is shown in Fig. 5. Their numbering increases with the length of the period with no ice cover.

A thermal classification of the Tatra lakes (Szaflarski, 1936) also consists of 7 groups, except that their

numbering increases with decrease in maximum water temperature. The significant coefficient of correlation in both classifications, which is close to -0.57 , results from the relationship between altitude and duration of ice cover as demonstrated by this study. In these two divisions, only group 5 of our classification and group 3 of the thermal classification (small lakes in the upper tree line zone/lower part of the subalpine zone) are fully consistent. Both groups include the same lakes. In J. Szaflarski's classification, the lakes of the second group have surface areas <1 ha, and they were not taken into account in our analysis. In the other cases, the discrepancies are significant (Fig. 6). It should be observed in this context that the classification of Tatra lakes published by J. Szaflarski was based on the compilation of the results of water temperature measurements carried out by him and other authors in different summer seasons. The study comprised a total of 29 lakes, of which only 19 have an area of >1 ha. In addition, some of the lakes assigned by J. Szaflarski to the various groups do not meet the classification criteria adopted by him. Furthermore, the study does not take into account the individual characteristics of many lakes.

The data about the ice cover of the Tatra lakes obtained through remote sensing can be compared to 1910-2010 data, which, however, only covers a dozen or so lakes altogether. As is revealed by the latter data (Fig. 7), in the early decades of the 20th century (Lityński, 1914; Pacl and Wit-Jóźwik, 1974; Gregor and Pacl, 2005), ice covered the Tatra lakes for ca. two more months on average than in the years 2014-2017. The largest and smallest differences in the duration of ice cover were observed for class 1 high-altitude lakes (Zamrznuté pleso)

and for unclassified low-lying, moraine and anthropogenic lakes (Štrbské plesa). However, it must be considered that efforts to document ice phenology undertaken in the Tatras in the early 20th century were far from systematic. In addition, the selection of lakes monitored in a given season was not always the same. Nevertheless, recent decades have not seen such long-lasting ice covers on the highest-lying lakes as at the time, which is consistent with the global multi-century trend of variability in ice cover (Sharma *et al.*, 2016). Compared to the 1999-2010 figures (Gądek and Szypuła, 2015), it can be seen that the ice cover on the lakes with an area >7 ha, mainly unclassified ones, lasted by an average of 2 weeks longer in the years 2014-2017. These observations correspond to the results of the monitoring of the ice cover on Morskie Oko conducted by the Institute of Meteorology and Water Management (IMGW) since 1971 (Choiński *et al.*, 2013; Gądek, 2014; Choiński *et al.*, 2015b; Wrzesiński *et al.*, 2016, Ptak *et al.*, 2017). The 1971-1979 data of the IMGW on the duration of the ice cover on Morskie Oko and Wielki Staw Polski (Choiński, 2017) confirm the interannual changes in the order of lakes ranked according to ice cover duration. The data shows that sometimes the ice cover on Wielki Staw Polski lasted for a shorter period than that on Morskie Oko, even though the former is located almost 270 m higher. Both the order of the freezing and of the thawing of both lakes changed. Notwithstanding the above changes, the average gradient of altitudinal ice cover duration did not show great variability over the last 100 years. Data obtained in the early 20th century (Lityński, 1914) prove that the gradient was close to 11 days/100 m, which means that it did not diverge much from the value determined in this

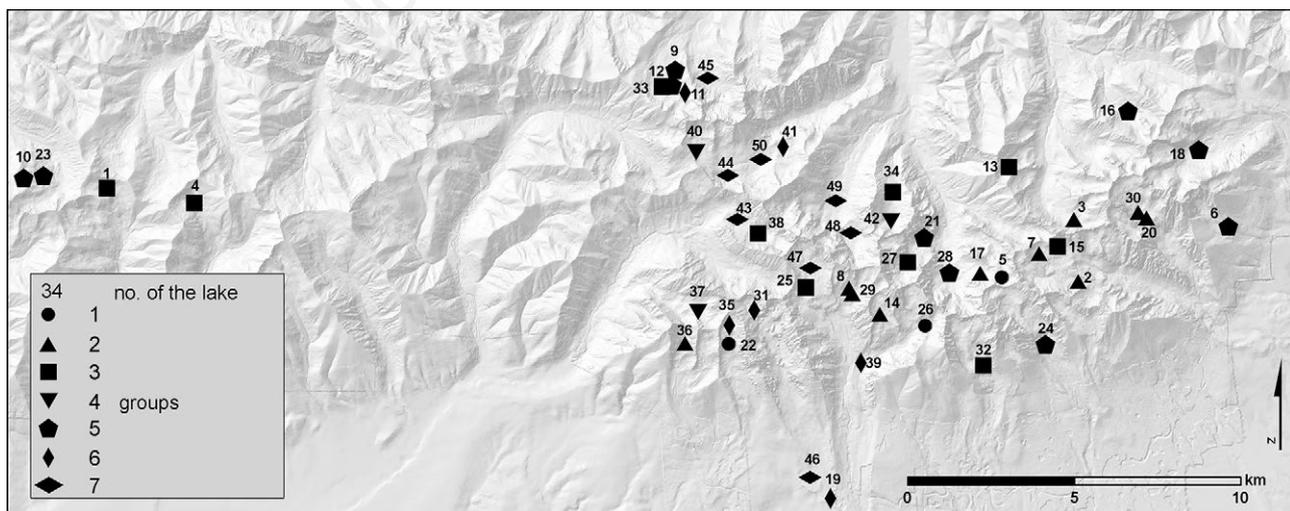


Fig. 5. Locations and groups of Tatra lakes. Numbers 1-7: lake groups (description in main text); numbering of lakes in accordance with the list in Tab. 1.

study, even though the number of lakes considered, the methods and the accuracy of observations in both cases were different. Also in the 2000/2001 season, the gradient exceeded 10 days/100 m (Šporka *et al.*, 2006).

The data obtained do not seem to confirm the relationship between ice cover duration and potential solar radiation identified by Novikmec *et al.* (2013). The correlation coefficient for these features was of a very low value. This may be attributable to the spatio-temporal variability of the local conditions of thermal balance of the lakes and of the development of ice cover (Blenckner, 2005). This variability is manifested, *inter alia*, by variations in the dates and order of freezing and thawing of

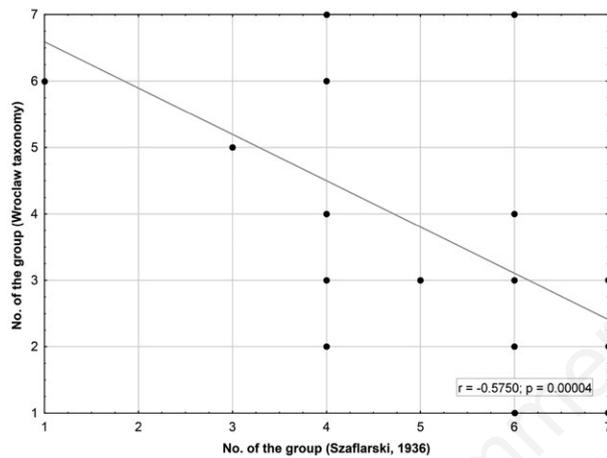


Fig. 6. Relationship between the lake groups determined by means of the Wrocław taxonomy and by Szaflarski (1936); black circles and numbers assigned to them: lake groups numbered in accordance with the list in Tab. 1. r , correlation coefficient; p , statistical significance.

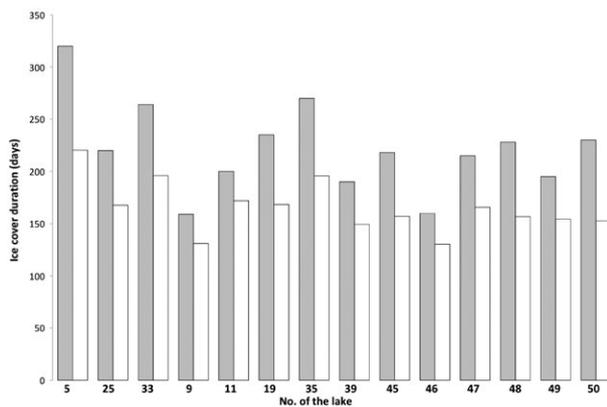


Fig. 7. Ice cover duration in the early decades of the 20th century (grey bars) and in 2014-2017 (white bars). The numbering of the lakes corresponds with the list in Tab. 1.

the lakes. The values of the annual totals of potential solar radiation calculated by us and by Novikmec *et al.* (2013) were very similar. The discrepancies stemmed from the different resolutions of the numerical terrain models. The DEM we used had a resolution of 10x10 m, while Novikmec *et al.* (2013) used a model with a resolution of 20x20 m. However, by using the Wrocław taxonomy method, we found that low insolation is one of the important features of group 1 lakes, while high solar radiation is characteristic of lakes in group 3 of the above classification.

CONCLUSIONS

1. High-mountain lakes can be grouped on the basis of the similarity of their altitude, morphometry and topographical conditions. These features are reflected by the duration of the ice cover of the lakes. However, many lakes can be characterised by far-reaching individuality (they are dissimilar from other lakes). In the Tatras, this is mainly seen with the largest lakes.
2. The strongest relationship displayed is that of ice cover duration with altitude. The relationship is noticeably weakened by variations in the volume of the lakes. Solar radiation can also have an effect on the duration of ice cover. Notably, the order of freezing and thawing of mountain lakes can also change from year to year. Therefore, determining the duration of the ice cover of lakes over several seasons facilitates the identification of the similarities and dissimilarities between them.
3. The duration of the ice cover on the Tatra lakes has been noticeably shortening over the last 100 years. The most rapid changes seem to be on small, high-altitude lakes. However, this observation needs to be verified.

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