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Diversity of epilithic diatoms in high mountain lakes under the stress of acidification (Tatra Mts, Poland)

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Using the epilithic diatoms as indicators of environmental conditions, 10 lakes in the High Tatra Mountains were characterised with regard to their stage of acidification. The diatom communities were diverse; 210 taxa were found, including 27 species of north and alpine preference. On the basis of cluster analysis, two groups of lakes were distinguished. The first group included shallow, moderately acidified lakes (Dlugi and Zmarzly Gasienicowy lakes), where acidophilous organisms prevailed, with *Achnanthes marginulata* being the most numerous. The structure of the diatom community in Dlugi lake was stable over 4 years of observations and did not show any progress in acidification. The second group included mostly very deep, non-acidified lakes where circumneutral organisms prevailed, and among them *Achnanthes minutissima* was dominant in most cases. The diatom community structures mostly confirmed the status of the lakes studied as judged from their water chemistry.

Keywords : mountain lakes, Tatra Mts, acidification, indicators, epilithic diatoms.

Introduction

Investigations on epilithic diatom communities living in lakes of the Tatra Mountains were carried out as part of different EU Projects: AL:PE2 (Alpine Lakes: Paleolimnology and Ecology), MOLAR (Mountain Lake Research), and EMERGE (European Mountain lake Ecosystems: Regionalisation, diaGnostics & Socio-economic Evaluation). Following the requirements of the EU Water Framework Directive, the aim of these programmes was to assess the status of remote mountain and arctic lake ecosystems throughout Europe. These remote environments, situated in the Alpine and Arctic regions of Europe, are far from local sources of pollution (e.g. land-use or waste-water pollution), and are consequently more sensitive to changes in air quality (acidity and toxic air pollutants). For the EMERGE investigations many alpine lakes situated in high northern latitudes at high altitudes more than 2000 m have been selected. They are distributed in 12 remote mountain Lake Districts (356 lakes) that cover most of the geographical and environmental gradients in Europe. In the Polish part of the Tatra Mountains, 13 lakes were studied.

The Polish part of the Tatra Mts is affected mainly by long-distance emissions from industrial regions in Upper Silesia, Czech Republic and Slovakia. Many papers have been published on the water chemistry of Tatra Mountains lakes showing their various stages of acidification (Wojtan & Galas 1994, Bombówna & Wojtan 1999, Galas 2002). The previous algological studies of lakes in the alpine zone of the Tatra referred mainly to the phytoplankton (Wołoszyńska 1917, 1934, 1935, 1936, 1939, Szklarczyk-Gazdowa 1960, Ettl *et al*. 1965, Siemińska 1970, Juriš & Kováčik 1987, Lukavský 1994, Dargocká *et al.* 1997, Fott *et al.* 1999), and much less to the benthic organisms, e.g. in sediments, on stones, or associated with aquatic macrophytes (Wasylik 1965, Kawecka 1966, Starmach 1973, Marciniak 1982, 1986, Galas *et al.* 1996). There are also only few papers dealing with epilithic diatoms of high mountain lakes from other regions (Tolotti 2001, Tolotti & Cantonati 2002, Šiško & Kosi 2002).

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In these multidisciplinary projects several parameters of the water chemistry and biota in high mountain lakes have been considered. From the biological aspect, the bacterio-, phyto- and zooplankton, epilithic diatoms, and benthic invertebrates have been studied (Wathne *et al.* 1997, Wathne & Rosseland 1999) to understand (AL:PE2) and to measure the dynamic of the response of mountain lakes to acid deposition (MOLAR), to assess the distribution of species and food-web structure in relation to environmental gradients within and between geographical regions (EMERGE). Diatoms are good indicators of environmental conditions, often used in water quality assessment (Whitton *et al.* 1991, 1996, Van Dam *et al.* 1994, Prygiel *et al.* 1999).

The aim of the present study was to assess the ecological status of 10 lakes situated in the High Tatra Mountains, with special regard to their stage of acidification, by using epilithic diatoms as indicators of environmental conditions against the background of water chemistry data.

Study area

The Tatra Mountains are the highest part of the Carpathian massive (2599 m) situated on the border between Poland and Slovakia. The investigations, presented in this contribution were carried out in the High Tatra - the eastern part of the mountain range. Ten lakes were selected, located in the alpine zone (the timber line lies at an elevation of about 1550 m), in the area of the Five Polish Lakes Valley, Rybi Potok Valley, and Gasienicowa Valley (Fig. 1). The catchment is composed of granite. The lakes investigated are situated at al-

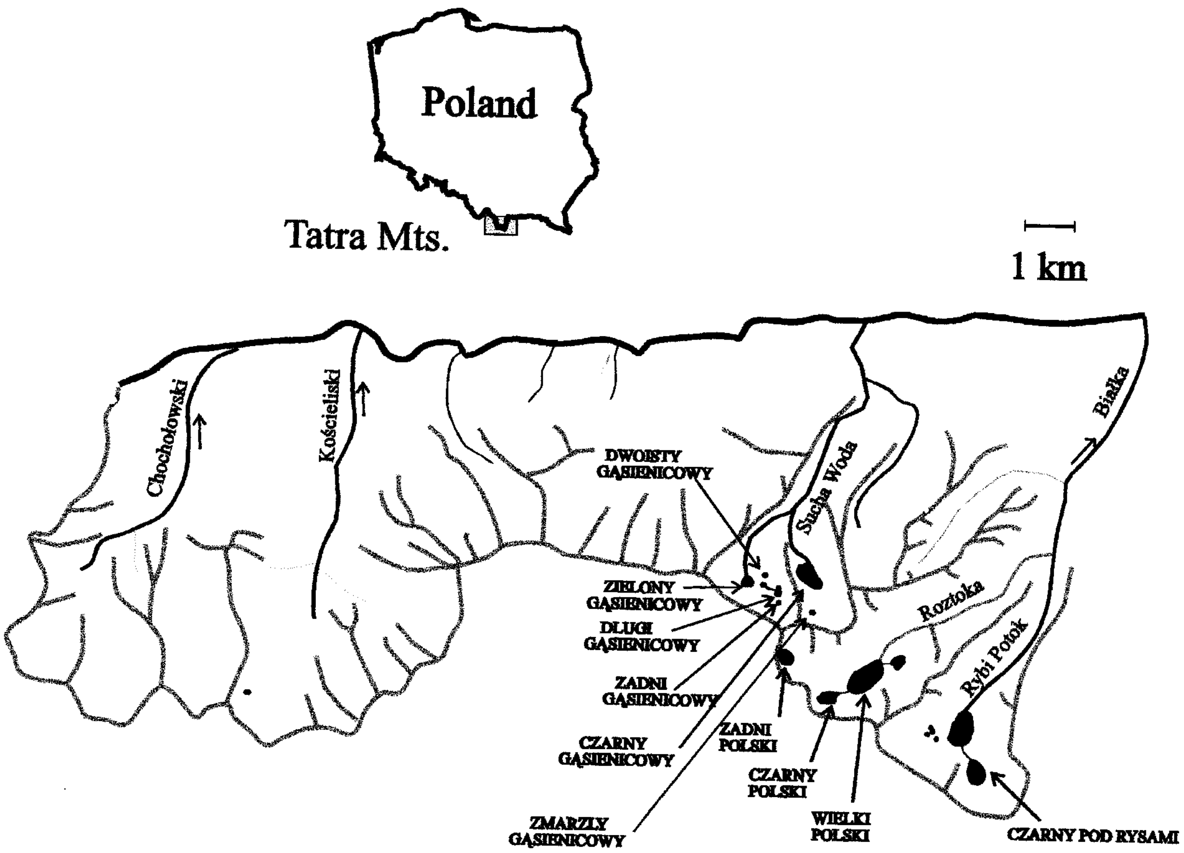

Fig. 1. Localisation of the studied lakes.

titudes from 1580 to 1890 m above sea level and differ in size (Table 1). The lake shorelines are rocky and only on the bottom of the Długi Gasienicowy lake the moss *Warnstorfia exannulata* (Schimp) Loeske develop extensively. Most of the lakes are filled with water throughout the year. They are fed mainly by precipitation and melting snow, but are also supplied by numerous springs and water draining through the rocky catchment. Only Dwoisty Gasienicowy (Eastern) lake, which is fed by a surface inflow of water coming mainly from melting snow, has an underground outflow which causes the complete disappearance of water under the snow cover in winter. The duration of the ice cover is 5-8 months.

Precipitation in the Tatra Mountains is mainly low in winter and higher in summer. The highest monthly input of water was recorded in June 1997 during a big flood (Galas 2002). The atmospheric deposition samples from the area of the Gasienicowa Valley were mostly acidic; in 80 % of samples the pH varied from 4.0 to 4.5; sulphate and nitrate concentrations were especially high (Table 2).

Methods

Precipitation was collected weekly in the Gasienicowa Va l l e y, while water samples were collected from the surface (10-20 cm depth) above the deepest point of each lake, in September 2000. Both lake water and precipitation samples were analysed according to the methods used in the EU programmes (The MOLAR Water Chemistry Group 1999). The epilithon samples from 10 lakes were collected once in September 2000. Only in the Długi Gasienicowy lake studies were carried out for several years. In this case the material was

Table 1. Morphometric characteristics of the studied lakes.

Lake name	Acronym	Altitude (m)	Area (ha)	Depth (m)	Residence time (year)	Littoral rock %	Littoral sand %	Littoral organic%
Czarny pod Rysami	CZR	1580	20.54	76.4	4.1	85	12	3
Zadni Polski	ZAP	1890	6.5	31.6	0.9	90	10	0
Czarny Polski	CZP	1722	12.7	50.4	4.1	85	12	3
Wielki Polski	WIP	1665	34.14	79.3	2.4	80	20	0
Zadni Gąsienicowy	ZAG	1852	0.53	8.0	0.05	95	5	0
Zmarzły Gąsienicowy	ZMG	1787	0.28	3.7	0.007	95	5	0
Długi Gąsienicowy	DŁG	1784	1.6	10.6	0.1	85	10	5
Zielony Gąsienicowy	ZIG	1672	3.8	15.1	0.7	80	15	5
Dwoisty Gąsienicowy	DWG	1657	1.4	9.2	0.2	90	10	0
Czarny Gąsienicowy	CZG	1620	17.79	51.0	1.7	80	15	5

Table 2. Ions concentration ($\mu eq.l^{-1}$) in atmospheric deposition.

Year	Volume (mm)	pH	Ca	Mg	Na	K	NH_4	NO_3	Cl	SO_4
1993 a	975	4.35	17	4	8	10	37	32	16	76
1994 a	1369	4.52	17	4	7	3	28	24	9	57
1995 a	1367	4.57	21	4	11	21	31	32	29	51
1996/1997 b	1684	4.24	16	5	4	-	24	28	-	79
1997/1998 b	1629	4.10	8	3	6	-	13	23	-	28

a: Lydersen et al.1997 ; b: The MOLAR Water Chemistry Group (1999) collected once a year in October of 1993 and 1994, in August and October of 1996, and in July and September of 1997. Usually 5 samples were taken from the bottom at ca. 40 cm depth, at different places along the lake shore. In July 1997, because of a much higher water level, assistance was provided by divers and the material collected at 1-2 m. Diatom epilithon was brushed from the whole upper surface of the several stones and was preserved with Lugol's solution. Subsamples for diatom analysis were macerated in sulphuric acid cleaning mixture, and then washed several times with distilled water by centrifugation. The cleaned diatoms were embedded in «Pleurax» synthetic resin (refractive index 1.75). The diatom taxa were identified and counted using a Nikon E 600 microscope.

The taxonomy of diatoms followed Krammer & Lange-Bertalot (1986-1991a, b), Round *et al*. (1990), Krammer (1992), Lange-Bertalot & Moser (1994), Lange-Bertalot & Metzeltin (1996), Lange-Bertalot *et al.* (1996), and Flower & Jones (1989). For quantitative elaboration of diatoms, a minimum of 250 valves per sample were counted along random transects. The percentage share of species in the communities was then calculated. The taxa with relative abundance lower than 5 % were designated as sporadic, the others as numerous.

The diversity index was calculated according to Shannon & Weaver (1949) formula, and evenness according to the formula of Pielou (1975) The division of diatoms into ecological groups with respect to water pH was conducted following the classification system of Van Dam *et al.* (1994). Diatom community results were processed using cluster analysis (Pearson correlation and average linkage methods).

Results

Lake water chemistry

The waters of the lakes studied were very weakly mineralised with low calcium and magnesium contents, and low alkalinity and conductivity values (Table 3). They were ultra- oligotrophic with very low contents of ammonium and nitrate. The pH varied from 5.7 to 7.0. Two groups of lakes depending on pH and ANC (Acid Neutralising Capacity), were distinguished, i.e. slightly acidified water bodies and non-acidified deep lakes (Table 3). The melting snow affects their water chemistry causing a decrease in alkalinity, pH, and major ion concentrations. Fluctuations of pH were observed during the year. The average pH value of the Dlugi Gasienicowy lake was 5.9, but during snow melt it dropped to 5.1 (Galas 2002). The lowest value of pH in Zielony Gasienicowy lake was recorded after snow melt period (4.2-4.5), while later on it slowly increased, reaching maximum values of 6.2-6.5 in summer (Kownacki *et al*. 2000). In Dwoisty Gasienicowy lake the pH fluctuated from 4.2 in June to 6.5 in August (Kownacki *et al*. 2002).

Table 3. Chemical characteristics of the studied lakes (conductivity $\mu S.cm^{-1}$ at 25° C; concentrations $\mu eq.l^{-1}$)*. ANC = Acid Neutralising Capacity. Differentiation on two group of lakes (slightly acidified, non acidified) according to Fott *et al*. (1994).

	pH	Cond.	Alk.	NH_4	Ca	Mg	SO_4	NO_3	Cl	ANC
Slightly acidified										
Zmarzly Gasienicowy	5.9	15	13	1.9	73	8	43	47	5.0	5
Dlugi Gasienicowy	6.2	15	22	3.1	71	7	46	34	4.8	18
Dwoisty Gasienicowy	5.8	13	[illegible]	3.8	61	14	43	31	4.9	20
Non acidified										
Zadni Polski	6.3	24	33	3.0	71	8	38	23	3.2	29
Zadni Gasienicowy	6.4	18	37	1.9	97	10	46	43	5.1	31
Czarny Gasienicowy	6.4	17	42	1.6	111	6	47	34	5.3	49
Czarny Polski	6.6	16	69	1.2	[illegible]	14	38	14	5.2	59
Wielki Polski	6.7	17	73	1.4	106	10	40	19	3.5	73
Zielony Gasienicowy	6.7	19	[illegible]	1.6	106	13	42	14	4.7	[illegible]
Czarny pod Rysami	7.0	28	137	1.0	189	12	57	31	5.3	124

* Stuchlik unpublished data

The structure of the diatom communities

210 diatom taxa were found in the material collected, and among them 27 species of north and alpine preference (Table 4). The most numerous genera were: *Navicula* (26 taxa), *Eunotia* (26), *Cymbella* (19), *Achnanthes* (19), *Fragilaria* (16), and *Pinnularia* (13). The highest species diversities (H') were observed in Zadni Polski and Zielony Gasienicowy lakes, while the lowest was in Czarny pod Rysami lake.

On the basis of comparative analysis of diatom communities investigated here, two groups of lakes were distinguished (Fig. 2). Zmarzły and Długi Gasienicowy lakes belong to group I whose diatom communities indicated a slightly acidic environment. Similarly, the values of pH (5.9- 6.1) and ANC (5-13) in these lakes classified them as intermediately acidified lakes. In their diatom communities, from 38 to 52 taxa were found, the diversity indices were medium and similar in both lakes (H' 3.2-3.6; evenness 0.63). Acidophilous organisms dominated (Fig. 3), with *Achnanthes marginulata, A. helvetica, A. helvetica* var. *minor* being the most numerous taxa (Fig. 4).

The 8 remaining lakes belonged to the second group, whose diatom communities did not indicate any acidification, as it was confirmed in most cases by their water chemistry. Only Dwoisty Gasienicowy lake had a slightly acidic character (Table 3). In other lakes, pH values varied from 6.3 to 7 and the ANC values from 29 to 124 which allowed them to be classified as non-acidified lakes. The numbers of taxa in these lakes ranged from 29 to 72, with fairly various diversity index values (H'1.6- 4.45; evenness 0.34-0.73). Circumneutral forms predominated, but alkaliphilous and acidophilous species were also fairly numerous, especially in Dwoisty Gasienicowy lake (Fig. 3). *Achnanthes minutissima* formed large populations, especially in Czarny pod Rysami lake, where it comprised approximately 80 % of the whole diatom community, which showed the lowest number of species and index of diversity. In other lakes, *Cymbella minuta, Fragilaria capucina* gracilis group, *Fragilaria pinnata*, species belonging to the genus *Achnanthes* (*Achnanthes curtissima, A. flexella, A. marginulata*), and *Diatoma ehrenbergii* were locally fairly numerous (Fig. 4).

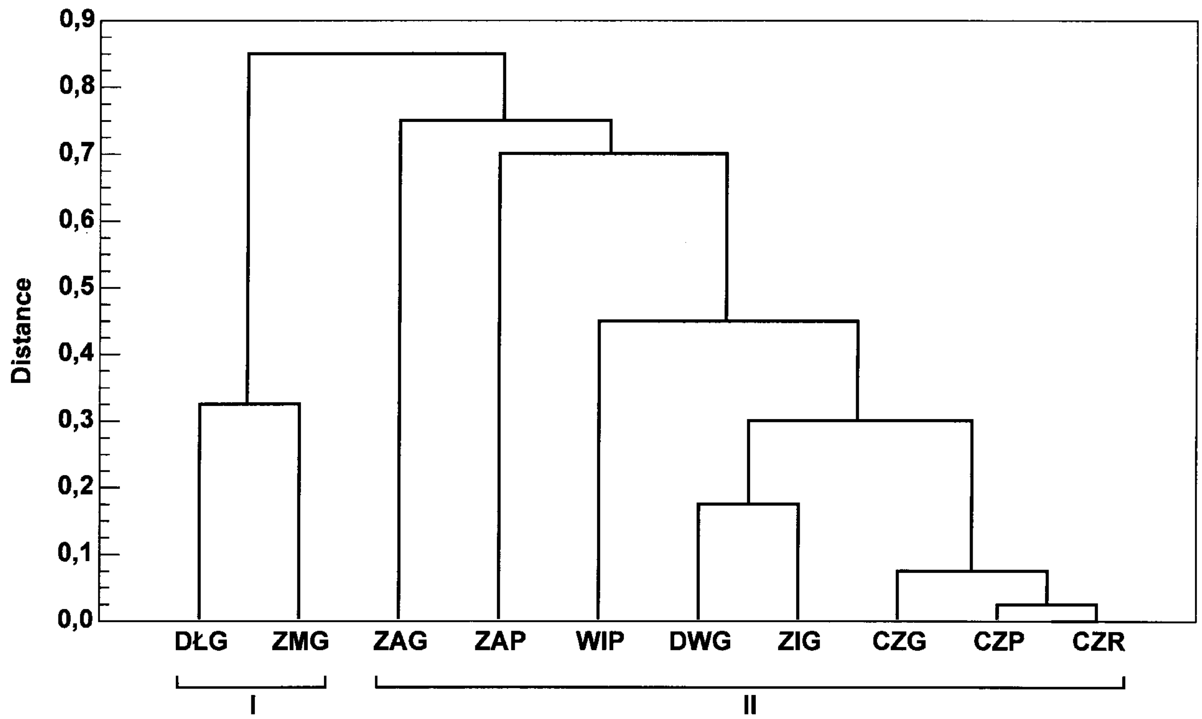

Fig. 2. Dendrogram of similarities between investigated lakes; group I: intermediately acidified lake, group II: non-acidified lakes (abbreviations : see Table 1).

Table 4. List of epilithic diatoms of investigated lakes; ++ = numerous species (> 5%), + = sporadic species, * = species with north and alpine preferences.

LOCATIONS	Rybi Potok Valley	Pięć Stawów Polskich Valley						Gąsienicowa Valley						
LAKE	Czarny pod Rysami	Wielki Polski	Zadni Polski	Czarny Polski	Zadni	Czarny	Zmarzły	Zielony	Dwoisty	Długi	Długi			
Taxon / Date	2000										1953	1994	1996	1997
Achnanthes biasolettiana Grun.				+	+							+		+
A. curtissima Carter	+	+	++	+		+	+			+	+	+	++	+
**A. didyma* Hust.			+											
**A. flexella* (Kütz.) Brun.	+	+		+		+		++	++		+	+	+	+
A. helvetica (Hust.) Lange-Bertalot	+	+		+		+	++		+	+	+	+	++	
A. helvetica var. *minor* Flower & Jones	+					+	++		+		+	+	+	
A. lacus-vulcani Lange-Bertalot & Krammer	+		+								+		+	
A. laevis Oestrup									+		+			+
A. lanceolata (Bréb.) Grun.								+				+	+	+
**A. lapidosa* Krasske			+		+	+		+	+		+		+	+
**A. levanderi* Hust.			+					+						
**A. marginulata* Grun.		+	+	+	+	++	++	+	+	++	++	++	++	++
A. minutissima Kütz.	++	++	++	++	++	++	+	++	++	++		+	++	++
**A. pusilla* (Grun.) De Toni			+											
A. scotica Flower			+				+	+	+	+		+	+	+
**A. subatomoides* (Hust.) L.-Bertalot & Archibald	+	+	+	+		+	+	+	+	+	+	+	++	+
A. suchlandtii Hust.	+	+												
**A. ventralis* (Krasske) Lange-Bertalot			+											
Achnanthes sp.					+		+	+				+	+	+
**Amphora fogediana* Krammer			+											
A. ovalis (Kütz.) Kütz.			+									+		
A. pediculus (Kütz.) Grun.	+		+		+	+		+	+			+		+
Amphora sp.													+	
**Aulacoseira alpigena* (Grun.) Krammer	+	+	+	+	+	++	+	+	+		+	+	+	++
A. distans (Ehr.) Simonsen v. *distans*	+	+			+					+				
A. granulata (Ehr.) Simonsen				+								+		
A. granulata var. *angustissima* (O.Müller) Simonsen												+		
A. islandica (O. Müller) Simonsen														+
A. lirata (Ehr.) Ross			+			+		+					+	
A. lirata (Ehr.) Ross var. *biseriata* (Grun.) Haworth		+		+							+	+	+	+
**A. valida* (Grun.) Krammer		+				+		+	+		+			
Aulacoseira spp.											+		+	+
**Brachysira brebissonii* Ross in Hartley		+		+		+	+	++	++	+	+	+	+	+
B. vitrea (Grun.) Ross		+	+	+		+		+	+				+	+
Caloneis aerophila Bock														+
C. bacillum (Grun.) Cleve														+
Chamaepinnularia soehrensis (Krasske) L.-Bertalot & Krammer var. *hassiaca* (Krasske) Lange-Bertalot											+	+	+	
Cocconeis pediculus Ehr.							+				+	+		
C. placentula Ehr.												+	+	+

Table 4. (Continued).

LOCATIONS	[illegible] Valley	[illegible] Valley						[illegible] Valley						
LAKE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			
Taxon / Date	2000										1993	1994	1996	1997
C. placentula Ehr.var. *euglypta* Ehr.	+	+		+	+	+	+	+	+	+	+	+	+	+
Craticula submolesta (Hust.) Lange-Bertalot											+	+		
Cyclotella meneghiniana Kütz.												+		
C. radiosa (Grun.) Lemmermann	+	+									+	+		
C. schumannii (Grun.) Håkansson														
Cyclotella spp.							+	+		+		+		
Cymbella affinis Kütz.		+	+		+									
C. amphicephala Naegeli														
C. cistula (Ehr.) Kirchner	+	+	+					+	+					
*C. cesatii (Rabh.) Grun.				+										
C. cymbiformis Ag.														
C. delicatula Kütz.	+													
*C. descripta (Hust.) Krammer & Lange-Bertalot					+		+							
C. elginensis Krammer			+											
C. gracilis (Ehr.) Kütz.		+		+										
*C. gaeumannii Meister			+											
*C. hebridica (Grun.) Cl														
C. helvetica Kütz.		+		+										
C. lanceolata (Ehr.) Kirchner		+	+											
C. minuta Hilse	+	+	+	+										
C. naviculiformis Auersw.														
C. perpusilla Cleve-Euler		+												
C. silesiaca Bleisch														
C. sinuata Greg.														
C. subaequalis Grun.														
Denticula tenuis Kütz.														
Diadesmis contenta (Grun.) D.G. Mann														
D. gallica W. Sm. var. *perpusilla* (Grun.) Lange- Bertalot		+	+	+		+		+	+	+	+	+	+	+
Diatoma ehrenbergii Kütz.					++						+			
D. hyemalis (Roth) Heib.		+							+		+	+	[illegible]	
D. mesodon (Ehr.) Kütz.		+		+	+	+	+	++	+	+	+	+		
D. moniliformis Kütz.												+		
D. tenuis Agardh											+			
D. vulgaris Bory Morphotyp vulgaris											+			
Diploneis ovalis (Hilse) Cl.			+											
Diploneis sp.														
Epithemia sp.														
Eunotia arcus Ehr.	+	+		+				+						
E. bilunaris (Ehr.) Mills				+			+	+						
E. bilunaris var. *linearis* (Okuno) Lange-Bertalot														
E. diodon Ehr.						+								
E. exigua (Bréb.) Rabenh.		++	+		+	+	[illegible]							
E. faba group														
E. fallax A.Cleve				+										
E. fallax var. *groenlandica* (Grun.) Lange-Bertalot & Nörpel														
E. glacialis Meister														
E. implicata Nörpel et al.														
E. incisa Greg.														
E. incisa boreoalpina group														
Eunotia incisa group														
E. intermedia (Krasske) Nörpel & Lange-Bertalot														
E. minor (Kütz) Grun.														

Table 4. (Continued)

LOCATIONS	Rybi Potok Valley	Pięć Stawów Polskich Valley						Gąsienicowa Valley						
LAKE	Czarny pod Rysami	Wielki Polski	Zadni Polski	Czarny Polski	Zadni	Czarny	Zmarzły	Zielony	Dwoisty	Litworowy	Długi			
Taxon / Date	2000										1993	1994	1996	1997
*E. muscicola Krasske var. tridentula Nörpel & Lange-Bertalot								+	+					
Eunotia nymanniana Grun.								+						
E. pectinalis (Dillwyn) Rabh.		+					+	+	+	+			+	
E. pectinalis var. *undulata* (Ralfs) Rabenh.													+	
E. praerupta sensu lato			+			+				+				+
E. praerupta Ehr.											+	+	+	+
E. praerupta bigibba group		+			+		+		+	++	+	++	+	+
E. praerupta curta group														+
*E. serra (Ehr.) Nörpel var. tetraodon Ehr.								+						
E. tenella (Grun.) Hust.											+	+	+	
Eunotia sp.													+	+
Eunotia [illegible]		+		+	+	+	+	+	+	+				
Fragilaria arcus (Ehr.) Cl.					++	+		+		+	+	+	+	+
F. capucina Desmazières	+	+			+	+			++	+	+		+	+
F. capucina gracilis group	+	++	+	+		+		++	+		++	+		+
F. capucina perminuta group			+											+
F. capucina rumpens group						+		+						
F. capucina vaucheriae group					+	+	+	+	+	+				
F. crotonensis Kitton											+			+
*F. exigua Grun.							+		+				+	+
Fragilaria cf. *exigua*			+	+		+		+						
F. fasciculata (Agardh) Lange-Bertalot												+		
F. pinnata Ehr.	+	+	++	+	+	+	+	+	+	+	+	+	+	+
*F. pseudoconstruens Marciniak	+	+	+			+	+							
*F. robusta (Fusey) Manguin	+				+			+						
F. ulna (Nitzsch) Lange-Bertalot	+		+		+	+			+			+	+	+
Fragilaria cf. *parasitica*												+		
Fragilaria spp.	+		+	+				+					+	
*Frustulia rhomboides (Ehr.) DeToni var. saxonica (Rabenh.) De Toni		+				+	+	+					+	
F. vulgaris (Thwaites) De Toni												+		
Gomphonema acuminatum Ehr.								+				+		
G. angustatum (Kütz.) Rabenh.			+					+			+	+		+
G. angustum Agardh	+	+	+	+	++	+	+	+	+	+	+	+	+	+
G. clavatum Ehr.	++	+		+			+		+	+	+	+	+	+
G. gracile Ehr.		+		+		+		+	+				+	+
G. olivaceum (Hornemann) Bréb.					+		+					+	+	+
G. parvulum (Kütz.) Kütz.	+	+	+	+		+		+	+			+	+	+
G. truncatum Ehr.		+		+		+		+	+		+		+	+
Gomphonema spp.					+				+					
Hantzschia amphioxys (Ehr.) Grun.			+		+					+	+	+	+	+
Hippodonta capitata Lange-Bertalot, Metzeltin & Witkowski								+				+		
H. hungarica (Grun.) Lange-Bertalot, Metzeltin & Witkowski								+						
Luticola goeppertiana D.G. Mann								+		+	+		+	+
L. mutica (Kütz.) D.G. Mann														+
Meridion circulare (Grev.) Ag.				+	+		+				+	+	+	
M. circulare var. *constrictum* (Ralfs) Van Heurck											+		+	
Muelleria gibbula (Cl.) Spaulding & Stoermer													+	
Navicula accomoda Hust.												+		
N. bacillum Ehr.			+											
N. capitatoradiata Germain			+									+		+
N. cryptocephala Kütz.		+	+				+				+		+	+
N. cryptotenella Lange-Bertalot			+		+		+	+					+	+
N. digitulus Hust.			++								+			

Table 4. (Continued).

LOCATIONS	Rybi Potok Valley	Pięć Stawów Polskich Valley						Gąsienicowa Valley						
LAKE	Czarny pod Rysami	Wielki Polski	Zadni Polski	Czarny Polski	Zadni	Czarny	Zmarzły	Zielony	Dwoisty	Litworowy	Długi			
Taxon Date	2000										1993	1994	1996	1997
N. angusta (Grun.) Grun.											+			
N. gregaria Donkin												+		
N. krasskei Hust.							+						+	+
N. lanceolata (Ag.) Ehr.		+								+		+	+	+
N. laterostrata Hust.			+											
N. minuscula Grun.			+									+		
N. pseudoscutiformis Hust.													+	+
N. pupula Kütz.														+
N. radiosa Kütz.				+	+		+				+			
*N. schmassmannii Hust.			++					+					+	+
N. schoenfeldii Hust.			+					+						
N. splendicula Van Landingham										+				
N. tripunctata (O.F. Müller) Bory							+					+	+	
N. trivialis Lange-Bertalot								+	+			+		
N. veneta Kütz.												+	+	+
N. viridula (Kütz.) Ehr.										+				
N. viridula var. rostellata (Kütz.) Cl.												+		
Navicula cf. [illegible]											+			
Navicula spp.		+		+	+							+	+	+
Neidium affine (Ehr.) Pfitzer		+	+		+			+			+			+
N. affine var. longiceps (Greg.) Cl.													+	+
N. affine group														+
N. alpinum Hust.													+	
N. bisulcatum (Lagerst.)		+	+	+	+	+	+	+	+	+	+	+	+	+
N. dubium (Ehr.) Cleve							+	+	+					+
*Neidium hercynicum (Hust.) Lange-Bertalot & Metzeltin									+			+	+	+
N. cf. dubium														+
Neidium sp.							+	+						
N. acicularis (Kütz.) W. Sm.												+		
N. amphibia Grun.												+		
N. alpina Hust.			+	+						+				
N. capitellata Hust.												+		
N. dissipata (Kütz.) Grun.			+		+							+		
N. fonticola Grun.			+									+		
N. gracilis Hantzsch												+		
N. hantzschiana Rabenh.											+		+	+
N. homburgiensis Lange-Bertalot											+			
N. linearis (Ag.) W. Sm.					+									
N. palea (Kütz.) W. Sm.					+							+		
N. recta Hantzsch												+		
Nitzschia spp.						+					+	+	+	+
Pinnularia appendiculata (Agardh) Cleve		+					+	+				+	+	+
*P. [illegible] Grun.														+
P. borealis Ehr.			+		+	+	+			+	+	+	+	+
P. divergens W.Sm.				+			+	+	+					
P. gibba Ehrenb.			+					+				+		+
P. interrupta W. Smith			+	+				+	+					+
P. microstauron (Ehr.) Cl.			+	+			+	+	+	+	+	+	+	+
P. microstauron Morphotyp 2		+	+				+				+	+		+
*P. obscura Krasske			+											
P. subcapitata Greg.		+	+	+	+	+	+	+	+		+	+	+	+
*P. sudetica (Hilse) Peragallo			+	+			+						+	+
P. viridis (Nitzsch) Ehr.		+	+				+		+		+			+
Pinnularia spp.													+	+
Rhoicosphenia abbreviata (Ag.) Lange-Bertalot			+							+		+		
Stauroneis agrestis Petersen		+												

Table 4. (Continued).

LOCATIONS	Rybi Potok Valley	Pięć Stawów Polskich Valley						Gąsienicowa Valley						
LAKE	Czarny pod Rysami	Wielki Polski	Zadni Polski	Czarny Polski	Zadni	Czarny	Zmarzły	Kurtkowiec	Dwoisty	Zielony	Długi			
Taxon Date:	2000										1983	1994	1996	1997
S. anceps Ehr.		+	+					+	+		+		+	+
S. phoenicenteron (Nitzsch) Ehr.			+						+	+	+			
Stauroneis sp.				+								+		+
Stenopterobia curvula (W.Sm.) Krammer												+		
Stephanodiscus alpinus Hust.				+						+			+	
S. hantzschii? Grun.														+
Surirella linearis W. Smith								+			+			
S. minuta Bréb.														+
Surirella sp.		+												
Tabellaria flocculosa (Roth) Kütz.	+	+	+	+	+	+	+	+	+	+	++	+		

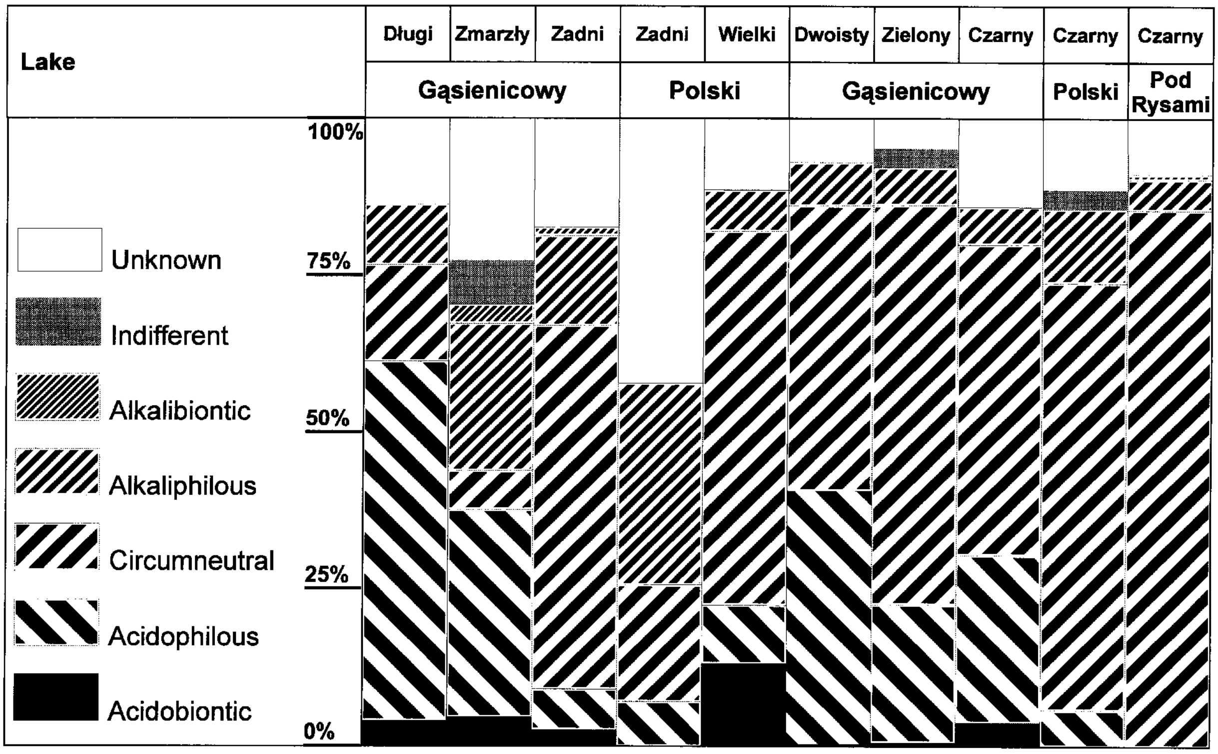

Fig. 3. Relative abundance of diatoms based on the pH classification system in investigated lakes.

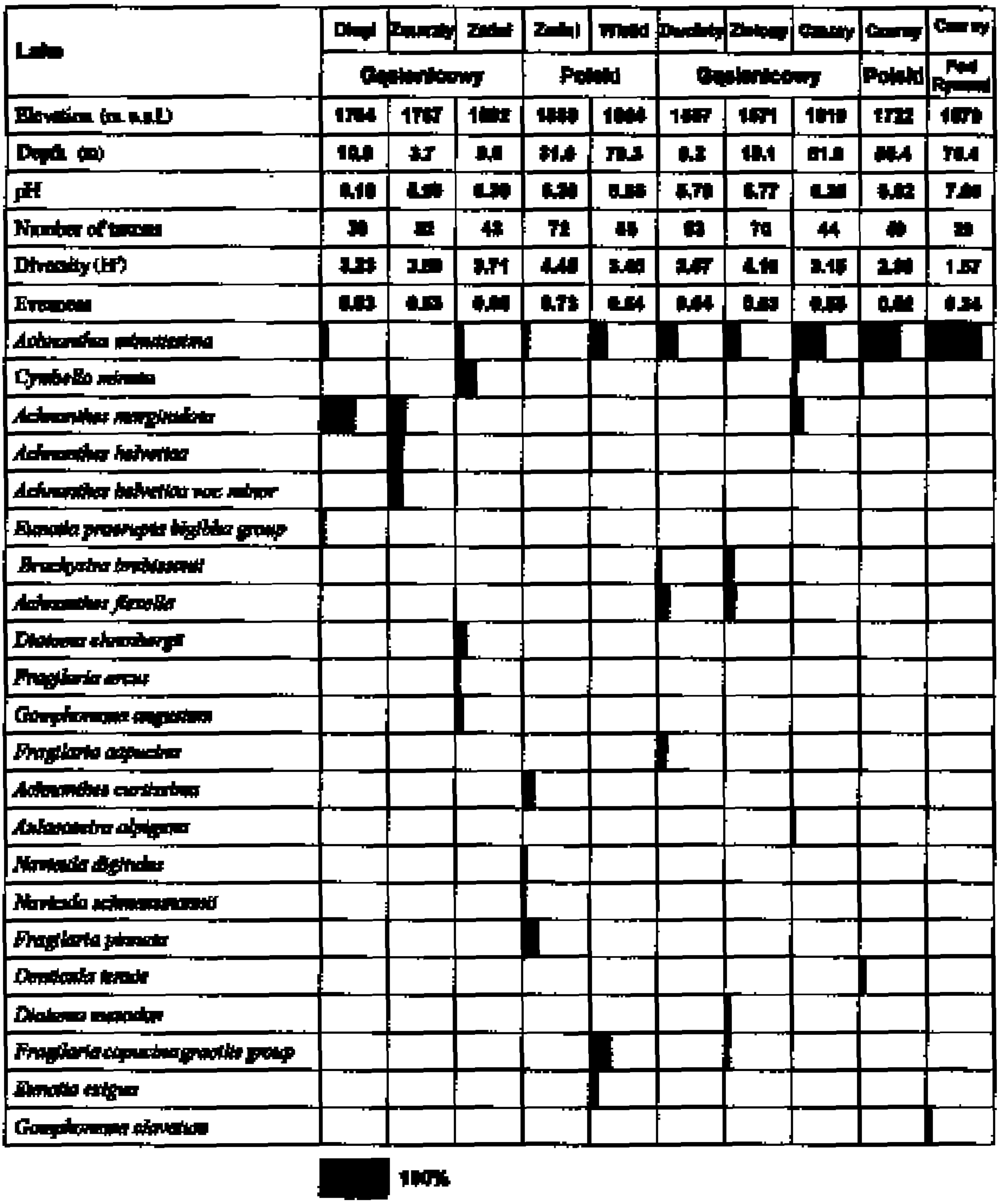

Fig. 4. The structure of diatom communities of investigated lakes; the numerous species (relative abundance > 5%).

S t r u c t u re of the diatom communities in Długi Gasienicowy lake during the years 1993-1997

Observations over four years indicated that diatom community structure in the Długi Gasienicowy lake was stable and did not show any change with respect to acidification. 171 diatom taxa were found, most of the species forming small populations. The diversity index was high and similar throughout the period of the investigations. Acidophilous groups of species dominated throughout (Fig. 5), the most abundant population being formed by *Achnanthes marg i n u l a t a*. Other *Ach - nanthes* species as *Achnanthes minutissima, A. subato - moides, A. curt i s s i m a* were also fairly numerous as well as *Cymbella minuta* and *Aulacoseira alpigena* (Fig. 6).

Discussion

The epilithic diatom communities and water chemistry of the lakes studied indicate that the majority of the Tatra lakes are not acidified (Tab. 3, Fig. 3, 4). Only two of them, shallow Długi and Zmarzły Gasienicowy lakes, show an intermediate level of acidification. In those lakes a group of acidophilous diatoms prevailed with *Achnanthes marg i n u l a t a* being dominant, reaching a particularly high percentage share of the diatom community in Długi Gasienicowy lake. *Ach - nanthes marginulata* is a species characteristic of oligotrophic waters, preferring weakly to moderately acidic waters (Krammer & Lange-Bertalot 1991 b). It is also numerous in small acidic Tatra water bodies such as Mnichowy Staw ponds (Kawecka unpublished data) which have a pH of 4.8-5.2 (Dumnicka & Galas 2002), as well as in lakes of several other high mountain regions e.g. in Norway, Scotland, Italy, and France (Wathne *et al.* 1995) whose pHs ranged from 4.5-6.1 (Mosello *et al.* 1995). It is worth noting that *Achnantes marginulata* is characteristic of the north-alpine areas (Krammer & Lange-Bertalot 1991b) and is an endan-

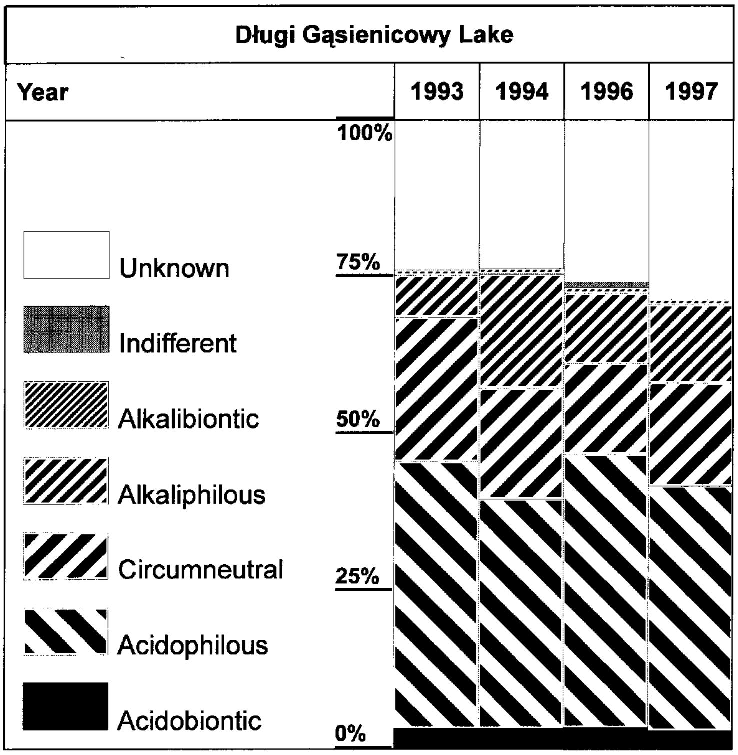

Fig. 5. Relative abundance of diatoms based on the pH classification system in Długi Gasienicowy lake in the years 1993-1996.

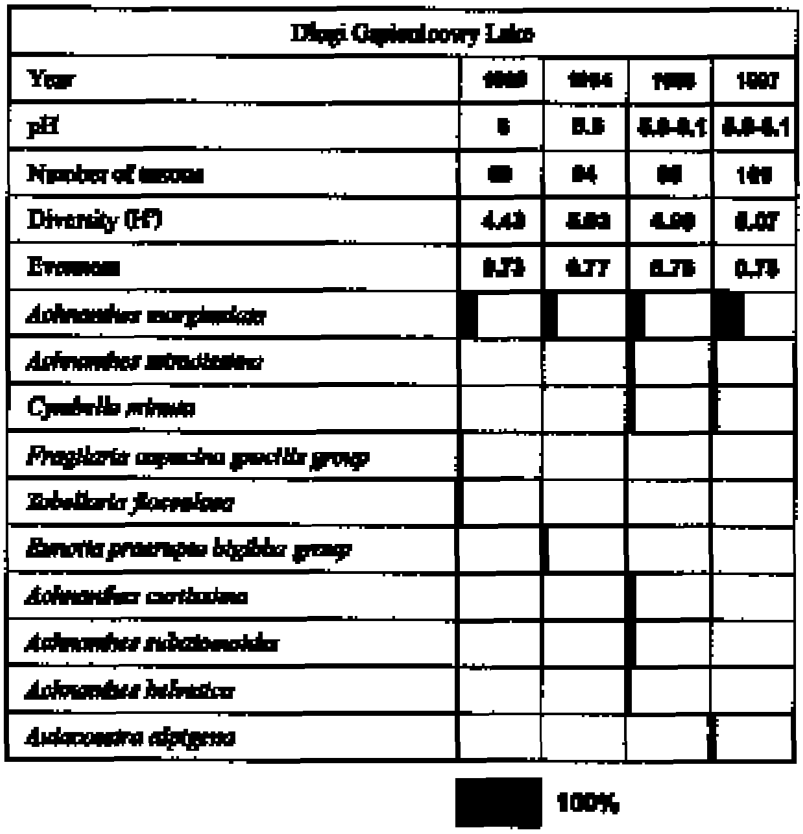

Fig. 6. The structure of diatom communities of Długi Gasienicowy lake in the years 1993-1996; the numerous species (relative abundance > 5%).

gered organism, included in the Red List of species (Lange-Bertalot & Genkal 1999). In Zmarzły Gasienicowy lake *Achnanthes marginulata* was accompanied by the also fairly abundant *Achnanthes helvetica* which prefers circumneutral to weakly acidic environments (Krammer & Lange-Bertalot 1991 b), and *A. helvetica* var. *minor*, another acidophilous organism (Flower & Jones 1989).

Four years' observations of diatom communities in Długi Gasienicowy lake showed a stability of structure, with dominance of *Achnanthes marginulata*, and did not indicate progress towards acidification (Fig. 5, 6), although long- term observations, made by several authors, of the pH of the lake water showed a small but gradual decline. Olszewski (1939) found the pH of the lake to be above 6, while 30 years later Oleksynowa & Komornicki (1989) noted a pH of 5,8. In the years 1985-1986 the mean pH value of the same lake was 5.6 (Wojtan & Galas 1994), with a similar value being noted from 1993 to 1999 (The Molar Water Chemistry Group 1999). At present, the moss *Warnstorfia exannulata* (Schimp.) Loeske, known for its preference in acid environments (peatbogs and swamps), is abundant on the bottom of this lake. However, the abundant development of a moss had already been noted in 1938 (Olszewski 1948). These findings therefore indicate that the intermediate acidic character of the water seems to be its constant and natural feature.

In the remaining mostly very deep lakes the circumneutral group of diatoms predominated, and among them *Achnanthes minutissima*, which has a wide ecological spectrum (pH 4.3-9.2; Lowe 1974) was numerous. It formed an especially large population in the deep Czarny pod Rysami lake, where the lowest diversity index was also recorded, which indicates some disturbance to the dominance structure of its diatom communities.

According to its water chemistry, Dwoisty Gasienicowy lake belongs to the group of intermediately acidic lakes. Within its diatom communities the circumneutral and acidobionts were in balance, but their structure did not indicate acidification. However, the structure of the diatom communities was not stable since the results of the 1996 study showed the dominance of *Achnanthes marginulata* and *Eunotia praerupta bigibba* group (Kownacki *et al.* 2002), which are both acidophilic organisms (Van Dam *et al.* 1994). This instability of its diatom community is connected with the ephemeral character of this lake from which the water disappears in winter through the underground outflow and, in spring, the lake fills again with water from the melting snow. Springtime is very important in the process of acidification, because the pH values drop drastically. The length of residence time is also an important factor in the acidification process (Kopáček & Stuchlik 1994). Such lakes as Dwoisty, Dlugi and Zmarzly Gasienicowy are especially threatened because their residence time is short and additionally they have very low alkalinity (Table 1, 3).

Conclusion

On the basis of water chemistry and diatom community structure analyses, most of 10 investigated Tatra lakes were not found to be acidified. To them belong the deep lakes where circumneutral organisms prevailed, and especially *Achnanthes minutissima* as the dominant species. Shallow lakes (Długi and Zmarzły Gasienicowy lakes) showed a moderate level of acidification. Acidophilous species prevailed there with the *Achnanthes marginulata* as the dominant species. Four years observations of the Długi lake indicate that acidification seems to be its constant feature. The diatom community structures generally confirmed the status of the studied lakes as judged from their water chemistry.

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