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SPATIAL VARIABILITY AND LONG-TERM CHANGES OF THE TROPHIC PARAMETERS IN THE GREAT MASURIAN LAKES (POLAND)

ABSTRACT: Hydrologic division of the Great Masurian Lakes (North-eastern Poland) into the northern and southern drainage basin was found to be reflected in different trophic status of lakes. Chlorophyll (but not nutrient) concentrations in the northern part of the system were significantly lower than those in lakes of the southern part. It has been shown that tunnel-valley lakes (numerous in the southern watershed) appear to be more eutrophied in terms of chlorophyll abundance than morainic stratified lakes. Hypolimnetic enrichment and internal loading were probably responsible for the lack of in-lake phosphorus and chlorophyll decline in spite of the evident decrease of the external nutrient loading which had taken place between 1985 and 1996. Such a positive response was observed, however, in the case of nitrogen. Only in a hypertrophic Lake Niegocin some symptoms of recovery were noted after reduction of external point source pollution.

KEY WORDS: chlorophyll, nutrients, internal loading, lake response.

1. INTRODUCTION

Long recognized problem of lake eutrophication still focuses attention of limnologists. Although trophic parameters of lakes generally follow Vollenweider's model (Vollenweider 1976) of chlorophyll - phosphorus relationships, there are too many deviations from this universal regression to be neglected. As already articulated (Reynolds 1992), regression model of chlorophyll response to nutrient variability is "an average of behaviours", which does not necessarily describe the eutrophication progress or recovery of a lake. In particular, biotic (algal) response

to nutrient reduction may depend on the mixing regime of a lake (Moss *et al.* 1997). Resuspension of bottom sediments, water transparency and internal nutrient loading are of similar or even greater importance than external nutrient input in controlling algal blooming in shallow lakes. That's why reduction of nutrient loading as a restoration measure seems to be less effective in shallow than in deep, stratified lakes (Sas 1989). In addition, algal abundance in some lakes may be effectively controlled by zooplankton grazing (Mazumder 1994a, b), which in turn

affects chlorophyll – nutrients relationships.

In some lakes the reduction of nutrient input results only in a decrease of in-lake nutrient concentration, in others it is accompanied by the decline in algal abundance and sometimes by the shift in specific structure of phytoplankton (Sas 1989). The later implies a lag time between nutrient alteration and the biotic response. Lake recovery after applying any restoration measures is not a simple reversion of man-made eutrophication. Instead, lake response follows the hysteresis curve as has been demonstrated at least for the

recovery of shallow lakes (Scheffer 1998).

All these complex factors involved make lake response to nutrient changes far from certainty. Still observed the weakness of predictive power of chlorophyll – nutrient models calls for more long-term measurements of the trophic parameters of lakes. This paper presents some results of a long-term monitoring performed in the Great Masurian Lakes system, which has been affected by various types of human activity and recently subject to a substantial reduction of the external nutrient inputs.

2. MATERIAL AND METHODS

2.1. STUDY AREA

Great Masurian Lakes (GML) system is the largest freshwater body in Poland stretching from Węgorzewo to Pisz ($54^{\circ}35,4'$ – $54^{\circ}10,9'$ N, $21^{\circ}33,4'$ – $21^{\circ}41,8'$ E, 116 – 119 m a.s.l. see Fig. 1). It consists of 30 lakes of various shape and size (Fig. 1, Table 1), total area of which is 310 km^2 . The lakes were interconnected in the seventeenth century to form a navigable lake system. Lakes of the system belong to the watershed of Węgorapa River to the north and to Pisa–Narew–Vistula Rivers to the south, the water division line passing usually across the town of Giżycko (Fig. 1) though the division may move according to water regime and artificially regulated outflow. The system delivers annually nearly 400 million m^3 to

Pisa River and ca. 300 million m^3 to Węgorapa River. The southern part of the system is fed by Krutynia River discharging its waters to Lake Beldany and by Jorka River with the outflow to Lake Tały. Central and northern parts of the system drainage basin are dominated by agriculture while southern part of the drainage is mainly forested. The whole Masurian region is one of the most important recreational sites in Poland. Therefore, the lake system is greatly affected by tourism concentrated around the towns of Giżycko, Ryn and Mikołajki. There is no heavy industry in the region, so the main threat to lake water quality is nutrient runoff from agriculture and from point pollution from the sewage outlet.

2.2. METHODS

Lake water was sampled from 1984 to 1996 with different intensity for different lakes (see Table 1). Water was sampled during spring overturn and in the summer

stagnation in triplicate from three layers: 1m below the surface, from the middle of the thermocline and 1 m above the bottom. Oxygen and temperature profiles as well

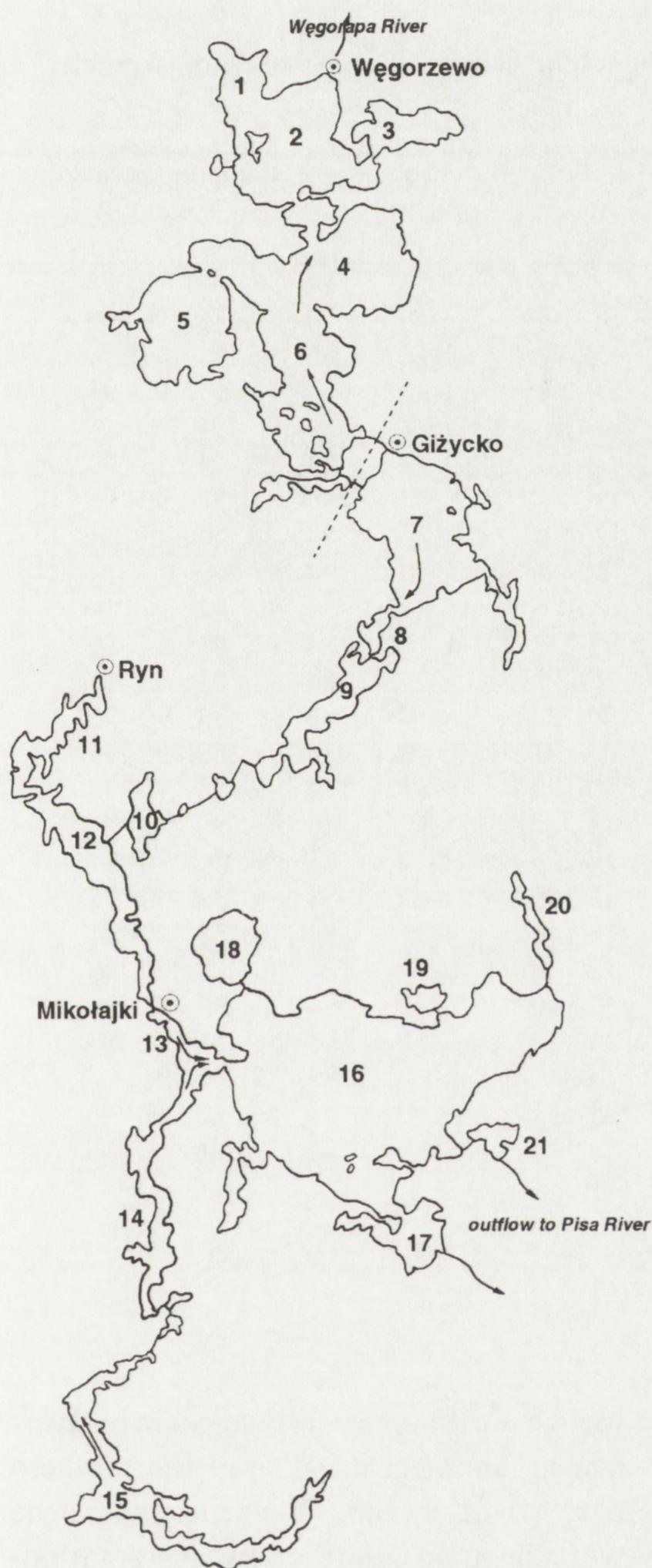


Fig. 1. A schematic map of the Great Masurian Lakes system. Dashed line is drawn along the water division line and arrows indicate water flow direction. Lakes: 1 – Przystań, 2 – Mamry, 3 – Świącajty, 4 – Dargin, 5 – Dobskie, 6 – Kisajno, 7 – Niegocin, 8 – Boczne, 9 – Jagodne, 10 – Tałtowisko, 11 – Ryńskie, 12 – Tałty, 13 – Mikołajskie, 14 – Beldany, 15 – Nidzkie, 16 – Śniardwy, 17 – Seksty, 18 – Łuknajno, 19 – Tuchlin, 20 – Tyrkło, 21 – Białołąwki. Lakes 8 – 15 and 20 are tunnel-valley basins and 16 – 19 are shallow, polymictic lakes

as Secchi disc visibility were measured while sampling. In the lab water samples were filtered through Whatman GF/C glass fiber filters. In the filtrate dissolved forms of Kjeldahl nitrogen (DKN) were measured with the method of Solórzano (1969) after the standard Kjeldahl combustion and dissolved phosphorus (DP) was analyzed with the molybdenum blue method after mineralization of the sample with perchloric acid (1 ml/50 ml of the sample). Nitrates were analyzed with phenyldisulphonic acid in filtered samples. Total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were measured with the same methods in unfiltered water samples. Total nitrogen is thus a sum of DKN and nitrate-nitrogen. Particulate nitrogen (PN) and particulate phosphorus (PP) were calculated as a difference between TKN and DKN and between TP and DP, respectively. Chlorophyll was analyzed in acetone extracts after Golterman (1969). After filtering a known volume of water, glass fiber filters were dried to a constant weight at a temperature of 105°C to estimate seston content.

3. RESULTS

3.1. SPATIAL VARIABILITY

Summer chlorophyll concentrations showed a distinct spatial pattern in the analyzed lakes. Generally lower chlorophyll content was found in the northern lakes drained by Węgorzapa River (Fig. 2, Table 2). Similarly low chlorophyll content was only found in some shallow lakes of the southern watershed. Chlorophyll concentrations increased also from Lake Nidzkie to Lake Beldany to Lake Mikołajskie reflecting water flow direction and the enlargement of the drainage basin area (Figs 1 and 2). The effect of increasing watershed area on lake trophic

Table 1. Morphometric and trophic characteristics of the sampled lakes. Numbers of lakes refer to those in Fig. 1.

No.	Lake	Area (ha)	Max. depth (m)	Mixing type ^a	TP ^b range (mg m ⁻³)	chl a ^c range (mg m ⁻³)	Sampling period (years)
1	Przystań	500	45.6	d	14-190	2-32	'84-'86, '88, '90-'96
2	Mamry	2004	47.0	d	35-100	3-10	'84-'86, '88, '90-'96
3	Święcajty	813	28.0	d	58-97	1-18	'85, '96
4	Dargin	3030	37.6	d	30-290	1-35	'84-'85, '91, '93-'96
5	Dobskie	1776	21.0	d	46-134	7-22	'84-'85, '95-'96
6	Kisajno	1896	25.0	d	60-150	3-17	'84-'85, '91, '93-'94, '96
7	Niegocin site 1	2600	39.7	d	137-830	13-60	'84-'86, '88, '90-'96
	Niegocin site 2				120-900	7-84	'84, '86, '88, '90-'96
8	Boczne	183	17.0	d	80-96	24-51	'84-'85, '96
9	Jagodne site 1	943	37.4	d	128-190	15-259	'84-'85, '91, '94, '96
	Jagodne site 2				75-255	11-121	'84-'85, '91, '94
10	Tałtowisko	327	39.5	d	120-358	6-39	'84-'85, '91, '93, '96
11	Ryńskie	620	47.0	d	50-122	26-71	'84-'86, '88, '90-'96
12	Tały site 1	1162	37.5	d	66-191	35-84	'85-'86, '88, '90-'96
	Tały site 2				30-175	6-81	'84-'86, '88, '90-'96
13	Mikołajskie	497	25.9	d	48-320	15-117	'86-'88, '90-'96
14	Beldany site 1	941	46.0	d	26-205	15-34	'86, '88, '90-'96
	Beldany site 2				22-125	14-43	'84-'86, '88, '90-'95
15	Nidzkie	1818	23.7	d	18-150	4-23	'84-'86, '88, '90-'96
16	Śniardwy	10970	23.4	p	12-170	5-29	'84-'86, '88, '90-'96
17	Seksty	370	6.3	p	32-140	11-42	'84-'86, '88, '90-'96
18	Łuknajno	680	3.0	p	34-139	3-40	'84, '86, '88, '90-'96
19	Tuchlin	219	4.9	p	10-67	8-59	'86, '88, '90-'96
20	Tyrkło	236	29.1	d	35-128	18-43	'84, '86, '88, '90-'96
21	Białoławki	211	36.1	d	24-122	8-25	'84, '86, '88, '90-'96

^a – d = dimictic, p = polymictic

^b – TP = summer epilimnetic total phosphorus

^c – chl a = summer epilimnetic chlorophyll a

status was not, however, noted in the southern part of the system from Lake Niegocin downstream. The highest average summer chlorophyll was recorded in the chain of the deep and narrow tunnel-valley lakes (Jagodne, Ryn, Tały and Mikołajskie) in the middle part of the system (Fig. 2, Table 3) while shallow lakes (e.g. Lake Śniardwy) and Lake Białoławki at the outflow from the system had low chlorophyll content.

Water transparency (measured as Secchi disc visibility) showed a reciprocal pattern to the chlorophyll spatial variability

being the highest (down to 4 m on average in summer) in lakes of the northern part of the system. It means that algae were the main contributor to water turbidity. Only in shallow lakes (Śniardwy, Łuknajno, Tuchlin and Seksty), due to sediment resuspension, water transparency was lower than one would have expected of the chlorophyll concentration.

Correlation between chlorophyll and nutrients was generally weak in the Great Masurian Lakes as demonstrated earlier (Kufel 1998). Accordingly, spatial differentiation of the chlorophyll concentra-

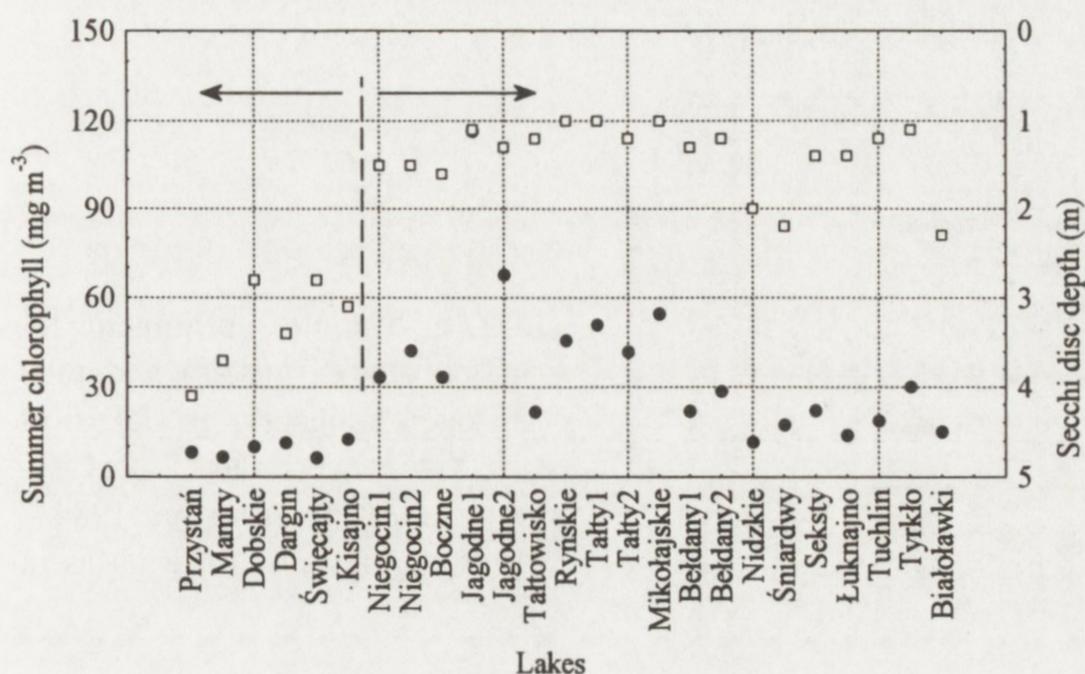


Fig. 2. Summer epilimnetic chlorophyll concentrations (dots) and summer Secchi disc visibility (squares) averaged over 1984–1996. Vertical line indicates water division line and arrows show water flow direction.

tions was not a plain reflection of nutrient concentrations in lake water. The latter did not show a clear spatial pattern in the analyzed lakes (Fig. 3, Table 2 and 3). The

these characteristics is hypolimnetic nutrient accumulation (measured as a difference between hypo- and epilimnetic nutrient concentration) which in turn de-

Table 2. A comparison of mean epilimnetic chlorophyll and nutrient concentrations in lakes of the two drainage basins

Parameter	Drainage basin of:		Statistics (Student <i>t</i> -test)
	Węgorapa River (6 lakes)	Pisa River (15 lakes)	
chlorophyll (mg m^{-3})	9.2	36.3	$P = 0.015$
TP (mg m^{-3})	90	123	$P = 0.393$
TN (mg dm^{-3})	1.31	1.57	$P = 0.168$

Table 3. A comparison of mean epilimnetic chlorophyll and nutrient concentrations in the morainic and the tunnel-valley masurian lakes (dimictic lakes only)

Parameter	Morainic lakes (8 lakes)	Tunnel-valley lakes (9 lakes)	Statistics (Student <i>t</i> -test)
chlorophyll (mg m^{-3})	18.3	47.1	$P = 0.008$
TP (mg m^{-3})	144	100	$P = 0.245$
TN (mg dm^{-3})	1.43	1.65	$P = 0.217$

highest nutrient concentrations were found in Lake Niegocin and in the tunnel-valley lakes but the differences between northern and southern part of the system were not so distinct as they were in the case of chlorophyll. Chlorophyll concentrations may depend on more complex characteristics of a lake than merely actual epilimnetic nutrient concentration. One of

termines an amount of possible internal nutrient loading. Hypolimnetic enrichment in phosphorus and epilimnetic chlorophyll show good agreement when compared in the analyzed Masurian lakes (Fig. 4). This relation appeals to the suggestion of Gliwicz and Kowalczewski (1981), who postulated that symptoms of eutrophication may evi-

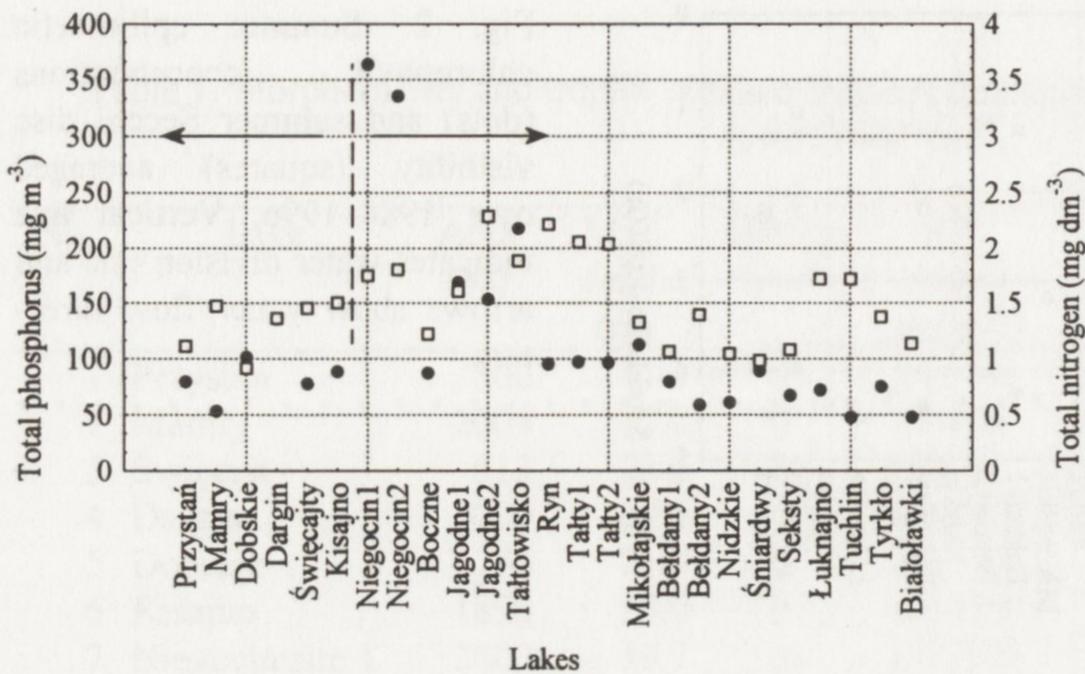


Fig. 3. Summer epilimnetic total phosphorus (dots) and total nitrogen (squares) in lakes of the Great Masurian Lakes system (mean values from 1984–1996). Lines and arrows – as in Fig. 2

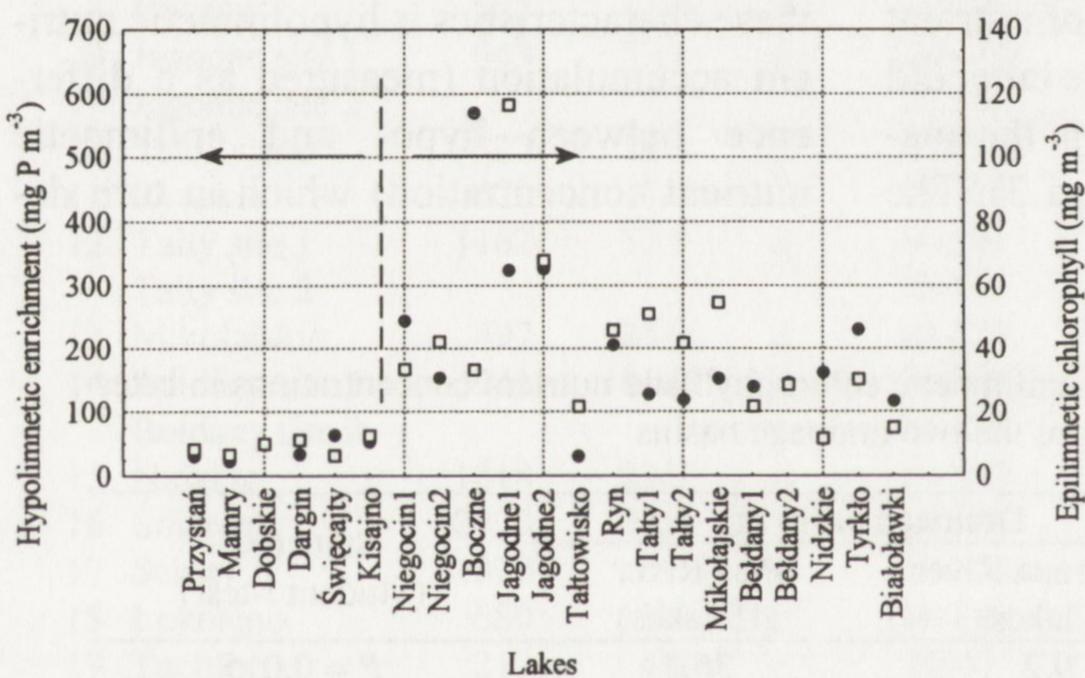


Fig. 4. Hypolimnetic enrichment in the total phosphorus (difference between hypolimnetic and epilimnetic TP concentration averaged over 1984–1996 – dots) and mean summer chlorophyll concentration (squares) in lake water.

dently manifest e.g. in hypolimnetic oxygen consumption. Additionally, it can be an evidence for the significant contribu-

tion of the internal phosphorus loading to the total nutrient loads to deep, tunnel-valley Masurian lakes.

3.2. LONG TERM CHANGES

Since the beginning of the nineties, economic changes in the watershed of the Great Masurian Lakes reduced the land impact on lakes. Due to the deep structural transformation in agriculture that had started in 1989, mineral fertilizer consumption, and thus also the surface nutrient runoff, decreased markedly. No data are available for particular watersheds or communes but data for the whole province (Fig. 5) demonstrate this process quite clearly. Point sources of the nutrient loading to lakes has been reduced as well. In

1994, tertiary sewage treatment was installed in Giżycko, the main source of point pollution to the GML system. This installation alone decreased annual P load to Lake Niegocin roughly by 0.29 g P m^{-2} (assuming 4 mg P dm^{-3} in previously treated domestic sewage and taking 1.3 mg P dm^{-3} in the tertiary effluents and $2.76 \times 10^6 \text{ m}^3$ as an average annual sewage outflow – Ochrona ... 1997) out of 0.89 g P m^{-2} of total load (Zdanowski and Hutorowicz 1994) from the direct drainage basin of the lake.

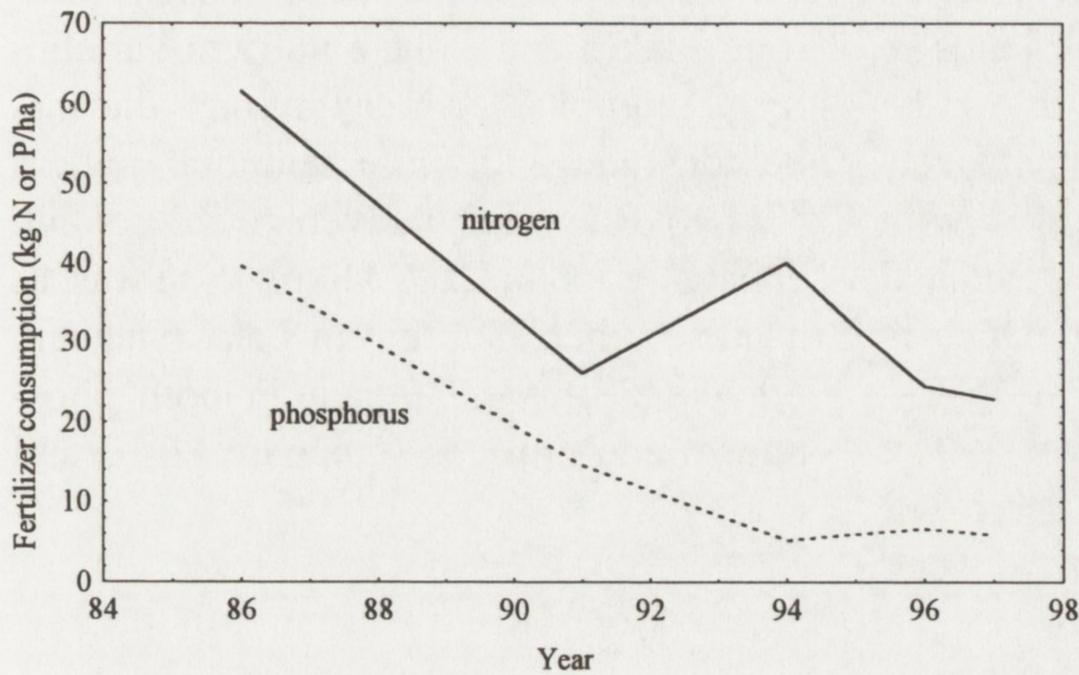


Fig. 5. Mineral fertilizer consumption (in kg nutrient per ha) between 1986 and 1997 in the Suwałki province (data from Ochrona ... 1997).

Such changes in the watershed management would have affected the nutrient level in lake waters. No significant temporal differences, however, were found in in-lake total P concentrations. If 1991 year be taken as a threshold date, then average TP (\pm SD) for all lakes were 120 ± 106 and 105 ± 128 mg P m⁻³, respectively for sampling period before and after that date. This lack of distinct lake response was manifested both in tunnel valley lakes represented in Fig. 6 by Lake Mikołajskie and in morainic lakes represented by Lake Mamry (Fig. 6). Only in Lake Niegocin after the peak concentration in 1992 (Fig. 6) epilimnetic phosphorus concentration gradually decreased onward most probably due to the reduction of point phosphorus sources. It seems again that in the deep

tunnel-valley lakes, internal P loading is more important to the lake nutrient budget than the external loading and hence reducing the latter did not influence lake water P concentrations. In contrary, Great Masurian Lakes were susceptible to variations in the external N loading. Summer epilimnetic total nitrogen concentrations were significantly ($P < 0.001$) lower after 1991 than before. N concentrations averaged (\pm SD) over the whole system were 1.79 ± 0.93 and 1.24 ± 0.50 before and after 1991 year, respectively. Due to relatively high variability of nitrogen concentrations and a low number of data (5–6 sampling dates for both compared periods) the significance of these differences can hardly be demonstrated for particular lake. The highest nitrogen concentrations in epilim-

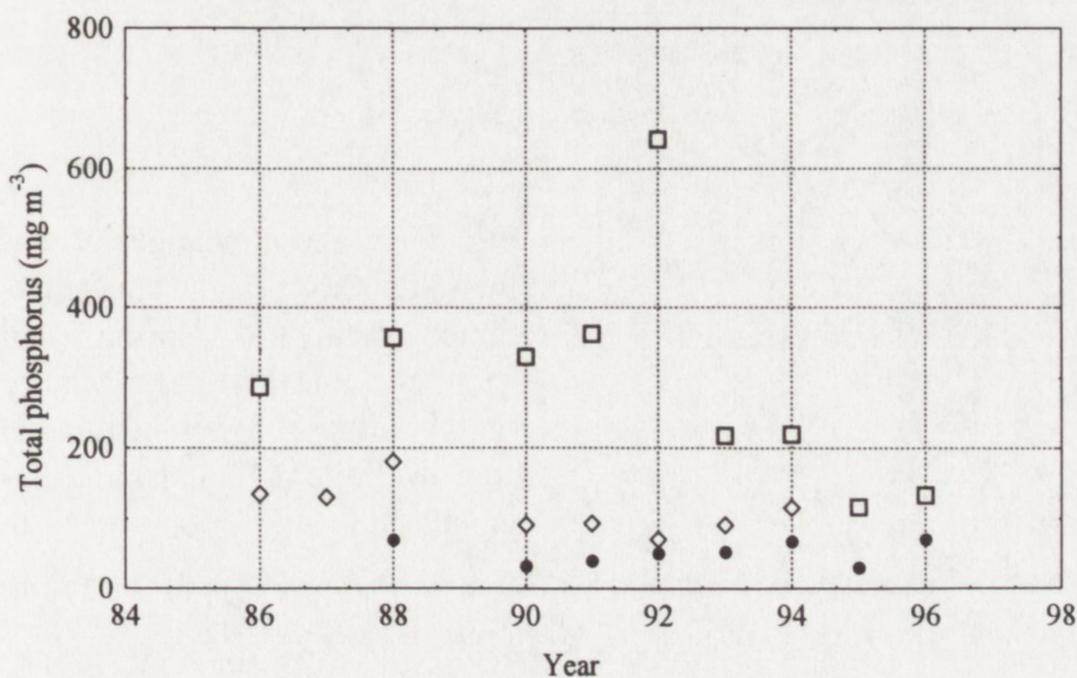


Fig. 6. Temporal changes of epilimnetic phosphorus concentration (mean of spring and summer values) were marked in Lake Niegocin (squares) only but neither in morainic Lake Mamry (dots) nor in the tunnel-valley Lake Mikołajskie (diamonds).

nia of lakes in 1990 and 1991 were ordered according to the share of arable lands in their watersheds (exemplified by Lake Beldany with the direct catchment forested in 83% to Lake Mikołajskie with 27% of arable areas in the direct watershed to Lake Ryńskie, watershed of which is used for agricultural purposes in 65% – Zdanowski and Hutorowicz 1994). Later on, total N concentrations decreased in these lakes and no distinction between the lakes could be visible (Fig. 7).

In spite of the reduced nutrient loading to lakes and in-lake nutrient variability, chlorophyll concentrations did not demonstrate a definite temporal pattern (Fig. 8). Remarkably, average chlorophyll concentration in Lake Mikołajskie was, as a rule, higher than that in Lake Niegocin otherwise more abundant in both phosphorus and nitrogen (compare Fig. 3 and Fig. 8).

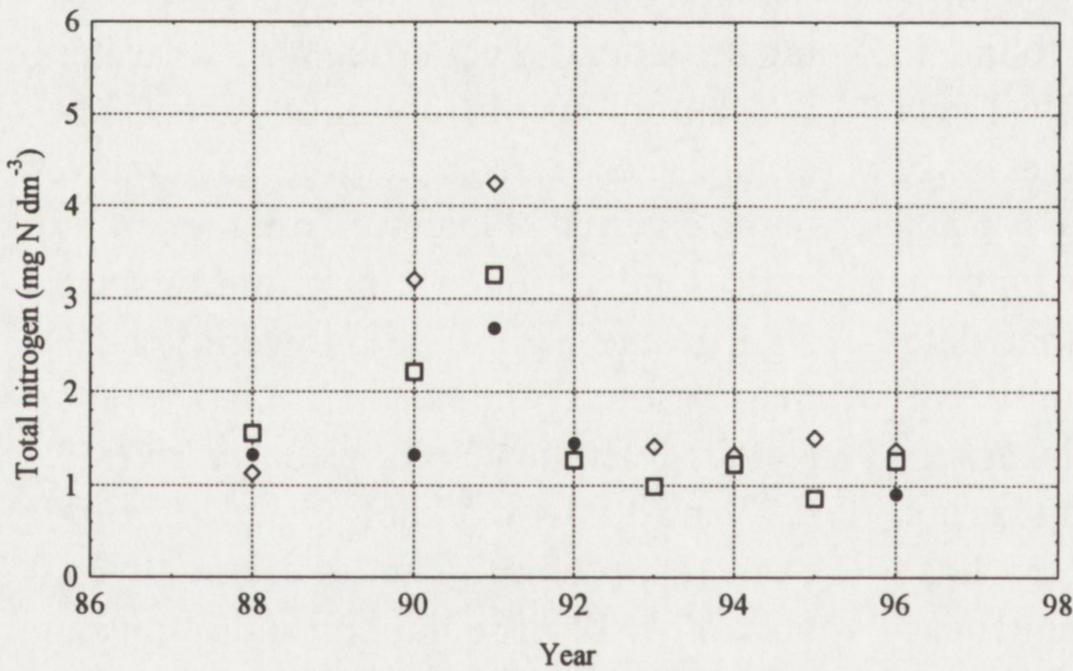


Fig. 7. Temporal changes of epilimnetic nitrogen concentrations (mean of spring and summer values) in the tunnel-valley lakes with the different degree of agricultural use in their watersheds. Dots – Lake Beldany, squares – Lake Mikołajskie, diamonds – Lake Ryńskie.

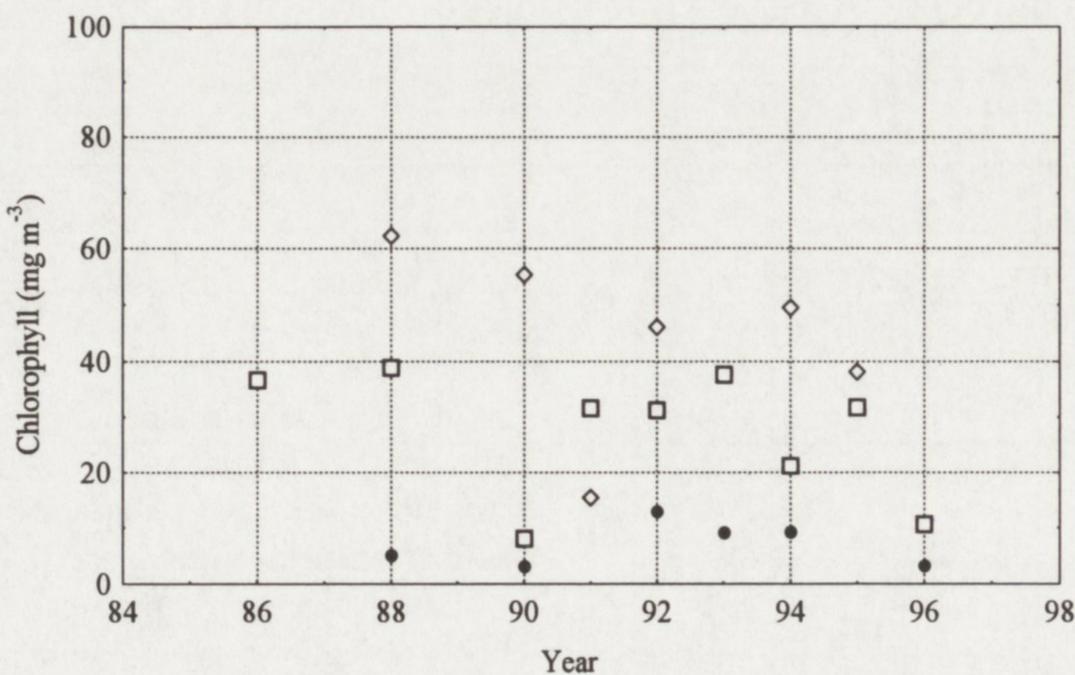


Fig. 8. Temporal changes of epilimnetic chlorophyll concentrations (mean of spring and summer values) in Lake Mamry (dots), Lake Niegocin (squares) and in Lake Mikołajskie (diamonds).

4. DISCUSSION

Due to the apparent uncoupling of chlorophyll and nutrients in the GML (Kufel 1998) reported also for lakes of the Suwałki Landscape Park (Hillbricht-Ilkowska 1993) it is not evident which of the parameters can better describe trophic status of lakes. It seems also that there is no single factor to explain chlorophyll (algal biomass) variability in the GML. Trophic status of the lakes is probably a resultant of overlapping various edaphic factors and morphometric features of particular lakes. The distinction between the northern and southern watershed of the GML system is clearly demonstrated in the different chlorophyll level but not in the nutrient content of lake waters (Figs 2 and 3). Distinct difference of chlorophyll content between the northern and southern parts of the system could be an effect of the presence of many tunnel-valley lakes in the latter. In spite of the similar average nutrient content, deep and narrow lakes showed on average higher chlorophyll concentrations than morainic lakes (Table 3). If assessed by the chlorophyll content, tunnel-valley lakes appear then to be more eutrophicated. The reason for this difference is not clear. One of the factors assumed to enhance trophic status of a lake is an area of the contact of epilimnetic waters with bottom sediments. Percent of the total bottom area within the reach of epilimnion was 64 in Lake Mamry but only 38 in Lake Tały and 31 in Lake Mikołajskie (Gliwicz and Kowalczewski 1981). In this aspect our results point to quite opposite conclusions. They are, however, in agreement with Gliwicz (1979), who demonstrated that steepness of the thermal gradient determines trophic status of lake epilimnia. In the tunnel-valley Masurian lakes vertical temperature gradients in

summer are certainly sharper than those in morainic lakes, which is reflected by apparently higher trophic status of the former as measured by the summer chlorophyll content (Table 3).

Higher chlorophyll content and at the same time similar average nutrient concentrations imply that nutrients are utilized more efficiently in the tunnel-valley lakes. Morainic and tunnel-valley lakes differed in the average depth of the mixing zone (11.3 m vs 9.6, respectively). It is possible that thinner and thus warmer mixing zone of the narrow elongated lakes provided better conditions for algal development, which manifested in generally higher chlorophyll concentrations. Less efficient mixing could in particular favour the growth of cyanobacteria, which were the main component of summer phytoplankton community in the GML (Kornatowska – personal communication).

Cumulative effect of the increasing watershed area on lakes is visible in the chain of lakes Nidzkie, Beldany and Mikołajskie. Increasing chlorophyll and nutrient concentrations along this sub-catchment is a reflection of both enlarged watershed area and an increase of arable lands in the direct watersheds of the lower lakes. This spatial pattern was not, however, observed in a part of the system that starts from Lake Niegocin. This lake receives large amounts of nutrients from point and diffuse sources and is rather a source of eutrophication for the lakes downstream (Boczne and Jagodne). Lakes in the northern subsystem, though much less affected by the land use impact, were not differentiated in nutrients or chlorophyll concentrations.

Reduced phosphorus loading to lakes did not result in marked changes in the trophic status in terms of phosphorus in-lake

concentrations (except perhaps Lake Niegocin) and in the chlorophyll content. Due to the significant internal P loading (as evidenced from high hypolimnetic P accumulation) lakes, especially the tunnel-valley lakes, still receive nutrient input large enough to support abundant algal growth. Nitrogen load does not seem to affect primary production in the GML sys-

tem. The reduction of external N loads and a decrease of N concentration in lake water was not followed by marked shift in chlorophyll content.

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5. SUMMARY

Great Masurian Lakes is a system of interconnected water bodies of various morphometric and trophic features (Fig. 1, Table 1). It is divided into the two drainage basins, which differ in the amount of external nutrient loading. The northern drainage basin is affected primarily by the agricultural surface runoff while the southern part is additionally supplied from point sources (sewage) and tourist impact. Lakes of the northern drainage basin were characterized by significantly lower average summer chlorophyll content than those from the southern basin (Fig. 2). This difference was, however, not manifested in in-lake nutrient concentrations (Fig. 3 and Table 2). Relatively high chlorophyll concentrations were noted in the deep tunnel-valley lakes (Table 3), which showed also a significant phosphorus enrichment of their hypolimnetic waters (Fig. 4). It seems therefore, that the dependence of algal abundance on nutrient availa-

bility is modified in masurian lakes by morphometric features of water basins.

In spite of significant reduction of diffuse (Fig. 5) and point sources of nutrient loading to lakes in the last decade, the response of lakes in terms of chlorophyll and in-lake phosphorus concentration was hardly noticeable (Figs 6 and 8). Only Lake Niegocin showed marked decrease in epilimnetic phosphorus concentrations after the installation of the tertiary sewage treatment (Fig. 6). Concentrations of nitrogen in epilimnetic waters responded to the decrease of external N loading, the response being proportional to the percentage of arable areas in the direct watershed of lakes (Fig. 7). Presented results suggest the importance of internal P loading in many masurian lakes, which is probably large enough to support extensive algal blooming still after the reduction of external nutrient sources.

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