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ECOLOGICAL CHARACTERISTICS OF LAKES IN NORTH-EASTERN POLAND VERSUS THEIR TROPHIC GRADIENT

V. CHLOROPHYLL CONTENT AND VISIBILITY OF SECCHI'S DISC IN 46 LAKES *

ABSTRACT: Chlorophyll content and visibility of Secchi's disc in spring and summer have been described for 46 lakes differing in their trophic state and mixis (dimictic and polymictic lakes). Chlorophyll content increased and visibility decreased along with increasing lake trophic state. For spring and summer the following relationships have been demonstrated: significant positive correlation between content of total phosphorus and chlorophyll, negative correlation between chlorophyll content and visibility, and less significant positive correlation between content of total nitrogen and chlorophyll in summer. No relationship was found between concentration of silicates and chlorophyll.

KEY WORDS: Lakes, trophic state, dimictic lakes, polymictic lakes, chlorophyll content, visibility of Secchi's disc, content of phosphorus, nitrogen and silicates.

C o n t e n t s

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1. INTRODUCTION

Chlorophyll content is widely applied as a trophic index (Solski 1962, Sakamoto 1966, Vollenweider 1968, Dillon and Rigler 1974a, 1974b, 1975, Sosnowska 1974, Smith 1979). Lake trophic state has also been determined by measuring visibility of Secchi's disc (Lasenby 1975, Bul'on 1977, Carlson 1977).

Some studies indicate (Schmidt-Van Dorp 1978, Smith 1979, Forsberg and Ryding 1980, Hickman 1980, Zdanowski 1982) that these indices are useful in an assessment of lake trophic state in a trophic gradient from oligo- to moderate eutrophy, that is, in situations where phosphorus is the main factor limiting primary production of lakes. In case of poly- and hypertrophic lakes this assessment is not unequivocal, probably due to the fact that the effect of many other abiotic and biotic factors on primary production varies considerably from lake to lake (Hillbricht-Ilkowska 1977, Zdanowski 1982).

In the present study variations in chlorophyll content and visibility of Secchi's disc were analysed for 28 dimictic and 18 polymictic lakes. Comparisons were made for spring circulation and summer stagnation periods versus variation of the lakes in respect to the content of total phosphorus, total nitrogen and silicates in the epilimnion.

2. MATERIAL AND METHODS

A total of 46 lakes found in the north-eastern Poland were selected for the study (Table I). Morphometry, trophic state and the degree of anthropogenic impact upon the lakes are described in the paper by Kajak and Zdanowski (1983). Data on chemistry of water are taken from Zdanowski's (1983a) paper.

On each lake visibility of Secchi's disc and chlorophyll levels were measured twice: after the disappearance of ice during spring circulation (April-May) and in the period of summer stagnation (August). Studies were carried out in 1977 and 1978. In the first year dimictic lakes were analysed, and in the second year - polymictic lakes of the pond type, and 4 dimictic lakes (Ełckie, Kokowo, Sztumskie and Wobel).

Chlorophyll was analysed in the epilimnion layer; determinations were made of the chlorophyll-a and phaeophytin contents (Lorenzen 1967). Water samples were filtered through Whatman GF/C filter-paper. The filters were subsequently dried and ground, and chlorophyll was extracted with 90% acetone. Extinction of chlorophyll-a and phaeophytins was read before and after sample acidification, on a "SPECOL" spectrophotometer, wave-length 665 and 750 nm.

The results are presented in Table I. Analyses were performed separately for dimictic and polymictic lakes. Three lake groups were distinguished for each mictic type, differing in their trophic state. The groups were distinguished on the basis of summer content of total phosphorus in the epilimnion (Table II). Summer level of total phosphorus in the dimictic lakes was as follows: group 1 - 0.020-0.044 mg $\cdot$ dm^{-3} (Gim, Kierzlińskie, Kuc, Leleskie, Ołów, Piłakno, Probarskie, Maróz, Sarż, Skanda), group 2 - 0.059--0.147 mg $\cdot$ dm^{-3} (Czos, Gromskie, Jaśkowskie, Lampackie, Sasek Duży, Szeląg Mały, Kalwa Duża, Rzeckie, Małszewo, Kokowo), group 3 - 0.175-0.506 mg $\cdot$ dm^{-3} (Ełckie, Juno Północne, Juno Południowe, Lidzbarskie, Sztumskie, Wobel), and in the polymictic lakes: group 1 - 0.054-0.092 mg $\cdot$ dm^{-3} (Burgale, Kołowin, Mój, Rańskie, Sędańskie, Siercze), group 2 - 0.134-0.285 mg $\cdot$ dm^{-3} (Brajnickie, Hartowiec, Sambród, Stryjewskie, Warpuńskie, Bądze, Sasek Mały, Długie), and group 3 - 0.321-0.940 mg $\cdot$ dm^{-3} (Liwieniec, Tuchel, Barlewickie, Iławskie, Kraksy Duże) (Tables I, II).

Table I. Content of total phosphorus, total nitrogen and chlorophyll, percentage of phaeophytin in the chlorophyll, and visibility of Secchi's disc in the epilimnion of dimictic (d) and polymictic (p) lakes in spring and summer

No.	Lakes	Spring					Summer				
		Tot-P ($mg \cdot dm^{-3}$)	Tot-N ($mg \cdot dm^{-3}$)	chlorophyll ($mg \cdot m^{-3}$)	phaeo-pigments in chlorophyll (%)	visibility of Secchi's disc (m)	Tot-P ($mg \cdot dm^{-3}$)	Tot-N ($mg \cdot dm^{-3}$)	chlorophyll ($mg \cdot m^{-3}$)	phaeo-pigments in chlorophyll (%)	visibility of Secchi's disc (m)
1	Barlewickie (p)	0.806	2.36	18.9	47	0.9	0.940	2.66	83.6	11	0.8
2	Bartąg (d)	0.054	1.22	6.8	68	2.9					
3	Bądze (p)	0.101	3.96	12.8	0	0.4	0.141	2.46	46.7	29	0.4
4	Brajnickie (p)	0.084	1.56	6.5	24	1.0	0.157	1.86	110.7	19	0.8
5	Burgale (p)	0.022	0.94			2.1	0.074	1.61	15.8	0	1.5
6	Czos (d)	0.095	0.59	38.0	22	2.0	0.068	1.25	17.9	93	2.4
7	Długie near Szczytno (p)	0.181	1.70	11.4	6	0.8	0.285	2.06	74.8	32	0.2
8	Ełckie (d)	0.140	2.06	2.1	50	3.0	0.202	1.86	46.7	67	1.6
9	Gim (d)	0.027	2.06	11.4	81	4.0	0.043	1.25	8.2	32	4.3
10	Gromskie (d)	0.039	1.40	4.6	0	2.0	0.066		5.1	50	
11	Hartowiec (p)	0.123	0.76	2.5	0	1.9	0.176	1.46	22.7	14	1.6
12	Jaśkowskie (d)					3.8	0.059	1.95	8.3	0	1.5
13	Iławskie (p)	0.255	1.16	47.5	34	0.7	0.420	3.56	167.5	73	0.6
14	Juno Północne (d)	0.314	1.98	13.2	32	3.2	0.175	2.00	32.8	4	1.6
15	Juno Południowe (d)	0.448	1.29	77.6	0	1.7	0.282	2.00	53.6	0	1.2
16	Kalwa Duża (d)	0.104	1.32	9.1	8	2.6	0.068	1.65	26.0	19	1.0
17	Kierzlińskie (d)	0.020	0.56	2.9	0	4.2	0.038	1.25	2.6	0	4.0
18	Kokowo (d)	0.100	0.82	8.5	67	0.6	0.147	1.51	18.7	26	1.1
19	Kołowin (p)	0.033	2.36			3.0	0.053	0.62	3.6	0	1.2
20	Kraksy Duże (p)	0.286	2.06	108.4	33	0.5	0.594	4.46	10.1	92	0.9

21	Kuc (d)	0.039	1.18	6.1	9	3.8	0.040	1.35	8.8	67	6.7
22	Lampackie (d)	0.062	1.48	28.0	86	2.0	0.073	1.00	17.0	34	2.0
23	Leleskie (d)	0.023	0.92	3.6	35	5.6	0.031	1.00	5.2	15	4.8
24	Lidzbarskie (d)					1.1	0.222		61.0	97	0.6
25	Liwieniec (p)	0.116	1.81	5.9	11	1.2	0.321	1.76	76.5	45	0.6
26	Małszewo (d)	0.057	0.70	19.5	19	1.3	0.137	1.35	33.7	30	1.3
27	Maróz (d)	0.085	1.20	24.2	13	2.5	0.040	0.95	9.2	0	3.6
28	Mój (p)	0.054	1.16	5.8	0	1.0	0.080	1.66	25.0	18	0.5
29	Ołów (d)	0.030	1.36	5.2	15	2.8	0.029	1.70	3.4	0	3.2
30	Piłakno (d)	0.020	1.62	3.4	10	3.4	0.020	1.25	1.5	0	9.0
31	Probarskie (d)	0.038	0.56	6.4	28	5.0	0.038	1.10	3.7	71	6.8
32	Rańskie (p)	0.058	2.01	24.0	0	0.9	0.092	1.46	17.0	0	1.1
33	Rzeckie (d)	0.080	1.40	5.5	0	3.2	0.087	1.75	36.6	43	2.7
34	Sambród (p)	0.086	1.26	11.3	28	1.1	0.161	2.26	77.8	23	0.4
35	Sarż (d)	0.047	1.70	4.2	0	3.0	0.031	1.55	4.8	28	1.3
36	Sasek Duży (d)	0.058	1.23	15.7	51	2.6	0.059	1.86	25.0	37	1.7
37	Sasek Mały (p)	0.169	1.82	16.7	48	0.8	0.142	3.26	55.3	29	0.6
38	Sędańskie (d)	0.052	1.82			2.3	0.090	1.66	31.3	31	1.0
39	Siercze (p)	0.046	0.83	2.9	50	1.5	0.084	1.16	13.7	13	0.5
40	Skanda (d)	0.050	0.93	12.6	34	2.3	0.044	1.00	11.7	11	2.9
41	Stryjewskie (p)	0.056	2.46	7.9	30	1.1	0.160	1.26	64.0	28	0.8
42	Szeląg Mały (d)					1.1	0.062	1.15	21.6	94	1.5
43	Sztumskie (d)	0.639	1.41	6.9	58	1.5	0.506	2.36	22.3	0	-
44	Tuchel (p)	0.082	2.66	11.9	22	1.0	0.357	2.56	236.7	23	0.5
45	Warpuńskie (p)	0.075	2.11	15.8	33	1.0	0.134	1.11	69.8	19	1.1
46	Wobel (d)	0.864	2.36	24.3	26	0.8	0.464	2.66	109.7	16	0.6

3. RESULTS

3.1. Changes in chlorophyll content

In spring, content of chlorophyll in the epilimnion in the dimictic lakes varied within a range of 2.1-77.6 $mg \cdot m^{-3}$. Low levels of chlorophyll (< 10 $mg \cdot m^{-3}$) were found in lakes of low trophic state: Gromskie, Kierzlińskie, Kuc, Leleskie, Ołów, Piłakno, Probarskie and Sarż, and in some lakes of high trophic state - Bartąg, Kokowo, Ełckie, Rzeckie and Sztumskie.

Percentage of phaeophytin in chlorophyll ranged from 0 to 86%, the average being 30%. The highest levels ($>$50%) were found in the following lakes: Bartąg, Gim, Lampackie, Sasek Duży, Kokowo and Sztumskie.

In shallow polymictic lakes, spring concentration of chlorophyll ranged from 2.5 to 108.4 $mg \cdot dm^{-3}$. High concentrations were found only in two fertile lakes, Iławskie and Kraksy Duże (47.5 and 108.4 $mg \cdot m^{-3}$, respectively). In the remaining polymictic lakes, spring content of chlorophyll did not exceed 24.0 $mg \cdot m^{-3}$.

In spring, percentage of phaeophytin in chlorophyll in the polymictic lakes showed a smaller range of variation (0-50%) than in the dimictic lakes, the average being 21%.

Average spring content of chlorophyll in particular trophic groups of the two mictic types was similar (Table II). In both groups concentration of chlorophyll increased along with increasing trophic state. This was accompanied by an increase in spring content of total phosphorus and a decrease in weight ratio of nitrogen to phosphorus. Average content of total nitrogen increased slightly with increasing trophic state only in the polymictic lakes (Table II).

In spring, significant positive correlation was found between content of total phosphorus and chlorophyll. The correlation coefficient was high and amounted to $r = 0.514$, at significance level of 0.05, and critical value at $n = 41$ and two degrees of freedom being 0.312. No significant correlation was found in spring between content of total nitrogen and chlorophyll, and between content of silicates and chlorophyll ($r = 0.258$, $r = 0.045$, respectively[1]).

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[1]Content of silicates was also taken into account, of these compounds could have affected variations in the content of chlorophyll in case of diatom predominance in the phytoplankton.

Table II. The mean and the range of variation of selected indices in spring and summer in dimictic and polymictic lakes, and in their three trophic groups differing as regards summer content of total phosphorus in the epilimnion

Lakes	Trophic group of lakes	Spring						Summer					
		Tot-P ($mg \cdot dm^{-3}$)	Tot-N ($mg \cdot dm^{-3}$)	N : P	SiO_2	chlorophyll ($mg \cdot m^{-3}$)	visibility of Secchi's disc (m)	Tot-P ($mg \cdot dm^{-3}$)	Tot-N ($mg \cdot dm^{-3}$)	N : P	SiO_2	chlorophyll ($mg \cdot m^{-3}$)	visibility of Secchi's disc (m)
Dimictic	1	0.038	1.18	33	5.2	8.0	3.7	0.036	1.24	39	5.3	5.9	4.7
		0.020-0.085	0.56-2.06	14-76	2.8-12.4	2.9-24.2	2.3-5.6	0.020-0.044	0.95-1.70	24-62	3.9-8.0	1.5-11.7	1.3-9.0
	2	0.074	1.12	17	8.7	16.1	2.1	0.084	1.49	23	6.8	21.0	1.7
		0.039-0.104	0.59-1.48	8-36	3.8-16.5	4.6-38.0	0.6-3.8	0.059-0.147	1.00-1.95	10-36	3.5-14.7	5.1-36.6	1.1-2.7
	3	0.481	1.81	6	6.0	24.8	1.9	0.309	2.18	8	3.8	54.3	1.1
		0.140-0.864	1.41-2.36	2-15	3.1-11.4	2.1-77.6	0.8-3.2	0.175-0.506	1.86-2.66	5-11	1.6-4.9	22.3-109.7	0.6-1.6
Polymictic	1	0.044	1.52	37	7.1	10.9	1.8	0.079	1.36	17	8.9	17.7	1.0
		0.022-0.058	0.83-2.36	18-71	6.0-11.1	2.9-24.0	0.9-3.0	0.054-0.092	0.62-1.66	14-22	5.7-17.7	3.6-31.3	0.5-1.5
	2	0.109	1.96	22	5.2	11.2	0.9	0.169	1.96	12	6.4	58.7	0.7
		0.056-0.181	0.76-3.96	6-44	3.1-11.2	2.5-16.7	0.4-1.9	0.134-0.285	1.46-3.26	7-23	3.6-10.0	22.7-77.8	0.2-1.6
	3	0.309	2.00	12	4.6	38.5	0.9	0.526	3.00	8	8.5	114.9	0.7
		0.082-0.806	1.16-2.60	3-32	2.7-7.7	5.9-108.4	0.5-1.2	0.321-0.940	1.76-4.46	3-19	4.6-15.0	10.1-236.7	0.5-0.9

Coefficient of multiple correlation (calculated with Doolittle's method; G u i l f o r d 1960), between content of chlorophyll and content of total phosphorus, total nitrogen and silicates equalled r = 0.516. It was significant at four variables at the level of 0.01. Its critical value, at n = 40, amounted to 0.494. The analysed chemical indices explained only small percentage of chlorophyll variation (26.6%). Phosphorus accounted for 25.8% of chlorophyll variation, nitrogen - only for 0.9%, and silicates - for as little as 0.1%.

Summer content of chlorophyll in the dimictic lakes varied between 1.5 and 109.7 $mg \cdot m^{-3}$. It was lower than the spring level only in lakes of the lowest trophic state (Table II). The highest content of chlorophyll was found in a fertile Lake Wobel and in some other lakes: Ełckie, Juno Północne, Juno Południowe, Lidzbarskie and Rzeckie (32.8-61.0 $mg \cdot m^{-3}$). Low chlorophyll levels were recorded for the following lakes: Gim, Gromskie, Kierzlińskie, Kuc, Leleskie, Piłakno, Probarskie, Sarż, Maróz and Jaśkowskie.

Percentage of phaeophytin in chlorophyll was 32% on the average, varying in particular lakes between 0 and 97%.

In the polymictic lakes, content of chlorophyll varied in summer between 3.6 and 236.7 $mg \cdot m^{-3}$. Its average level in particular trophic groups was higher in summer than in spring (Table II). This increase was accompanied by a growth of the average concentration of total phosphorus in summer, and a lowering of the nitrogen to phosphorus ratio, as also a decrease in average visibility (Table II). The highest levels of chlorophyll were recorded for Iławskie Lake and Lake Tuchel (167.5 and 236.7 $mg \cdot m^{-3}$). High chlorophyll concentrations (46.7-110.7 $mg \cdot m^{-3}$) were also recorded in the following lakes: Barlewickie, Bądze, Długie, Liwieniec, Sambród, Sasek Mały, Stryjewskie and Warpuńskie. At that time extremely low levels of chlorophyll were found only in two lakes, i.e., Lake Kołowin (3.6 $mg \cdot m^{-3}$) and a very fertile Lake Kraksy Duże (10.1 $mg \cdot m^{-3}$).

A high proportion of phaeophytin in the chlorophyll was found in summer only in Lake Kraksy Duże (92%). In the remaining polymictic lakes it ranged from 0 to 45%, being 18% on the average.

In summer, in lakes of both mictic types, and in their trophic groups, content of chlorophyll increased along with increasing lake trophic state (Table II). In the third trophic group of dimictic lakes the content of chlorophyll was about 9 times higher than in the first group, and in polymictic lakes - about 15 times higher. As the lake trophic state increased, there was an increase in summer content of total nitrogen, and a lowering of the nitrogen to phosphorus ratio.

In summer period, a highly significant positive correlation was found between level of total phosphorus and chlorophyll. The correlation coefficient was r = 0.756, at significance level of 0.001. Linear regression of this correlation was concordant with the tendency described by Z d a n o w s k i (1982). It slightly differed in the upper range of its variation from the tendency described by S c h i n d l e r (1978) and Z d a n o w s k i (1982) for lakes characterized by N : P ratio greater than 10 (Fig. 1), in which phosphorus and not nitrogen was the eutrophogenic factor.

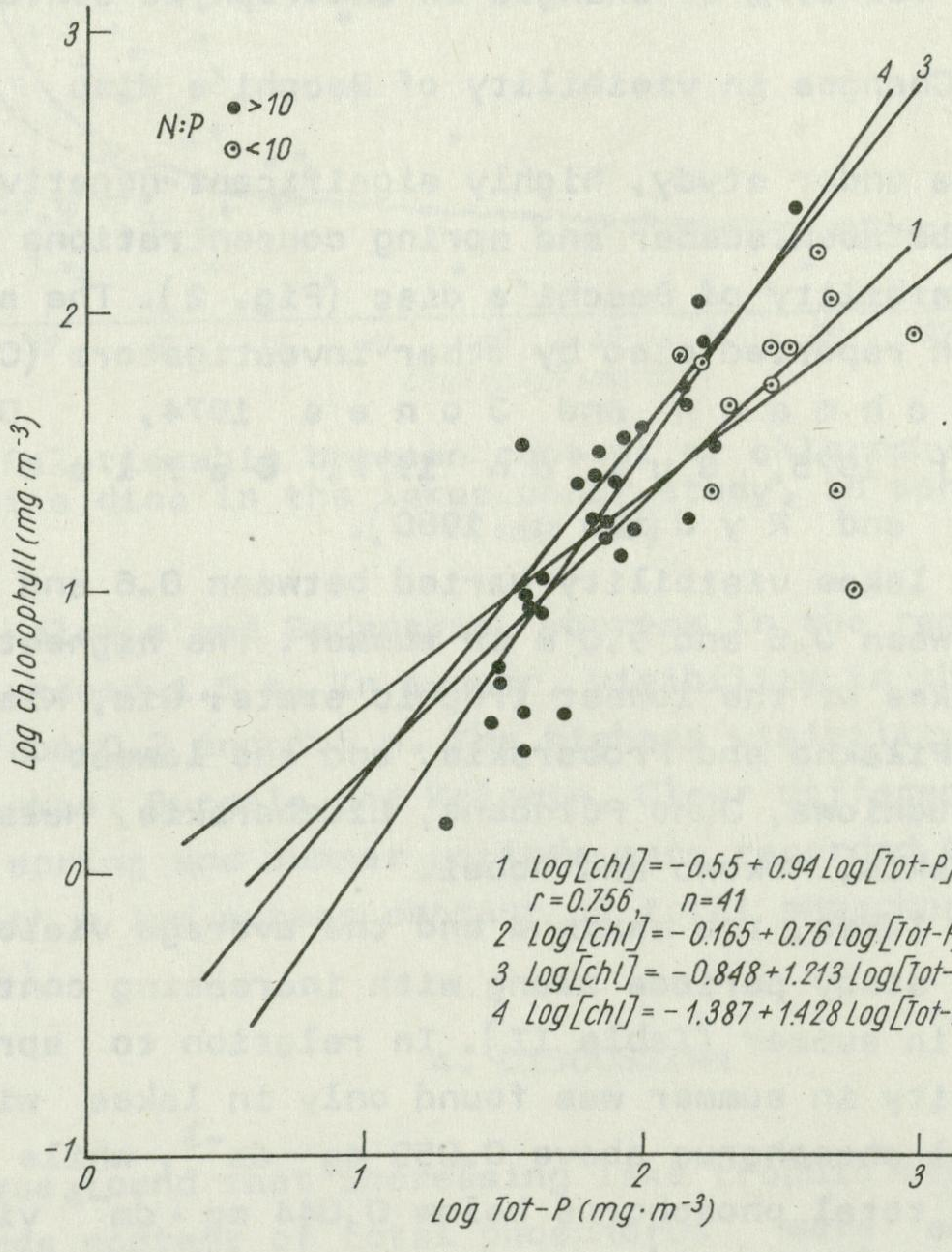

Fig. 1. Comparison of the relationship between content of total phosphorus and content of chlorophyll in the lakes under study in summer (1) with the relationships between these parameters in lakes: with an N : P ratio of 5-137 (2 - acc. to Z d a n o w s k i 1982) and an N : P ratio greater than 10 (3 - acc. to S c h i n d l e r 1978; 4 - acc. to Z d a n o w s k i 1982)

Summer period was additionally characterized by significant positive correlation between content of total nitrogen and chlorophyll (r = 0.493). As in spring, there was no significant relationship between content of silicates and chlorophyll (r = -0.103).

Summer period was also characterized by highly significant positive multiple correlation between content of chlorophyll, and content of total phosphorus, total nitrogen and silicates. The coefficient of correlation r = 0.775, is significant at the level of 0.01. Its critical value, at n = 40 equals to r = 0.491. Phosphorus, nitrogen and silicates jointly accounted for 60.1% of chlorophyll variation, that is, over twice as much as in spring. This time important role was played also by phosphorus, which accounted for 55.6% of chlorophyll variation. Total nitrogen accounted for 2.8%, and silicates - for 1.7% of changes in chlorophyll content.

3.2. Changes in visibility of Secchi's disc

In the lakes under study, highly significant negative correlation was found between summer and spring concentrations of chlorophyll, and visibility of Secchi's disc (Fig. 2). The same tendencies have been reported also by other investigators (C z e c z u g a 1964, B a c h m a n n and J o n e s 1974, D i l l o n and R i g l e r 1975, B u l'o n 1977, C a r l s o n 1977, F o r s b e r g and R y d i n g 1980).

In dimictic lakes visibility varied between 0.6 and 5.6 m in spring, and between 0.6 and 9.0 m in summer. The highest visibility was found in lakes of the lowest trophic state: Gim, Kierzlińskie, Leleskie, Kuc, Piłakno and Probarskie, and the lowest - in fertile lakes: Juno Południowe, Juno Północne, Lidzbarskie, Małszewo, Szeląg Mały, Sztumskie, Kokowo and Wobel.

In dimictic lakes, the maximum and the average visibility decreased in both study periods along with increasing content of total phosphorus in summer (Table II). In relation to spring lower average visibility in summer was found only in lakes with summer content of total phosphorus above 0.059 $mg \cdot dm^{-3}$, while in lakes with content of total phosphorus below 0.044 $mg \cdot dm^{-3}$ visibility in summer was higher (Table II).

In polymictic lakes, as a rule mixed down to the bottom, spring visibility ranged from 0.4 to 3.0 m. Higher visibility (1.9-3.0 m) was found in this period only in the following lakes: Burgale, Har-

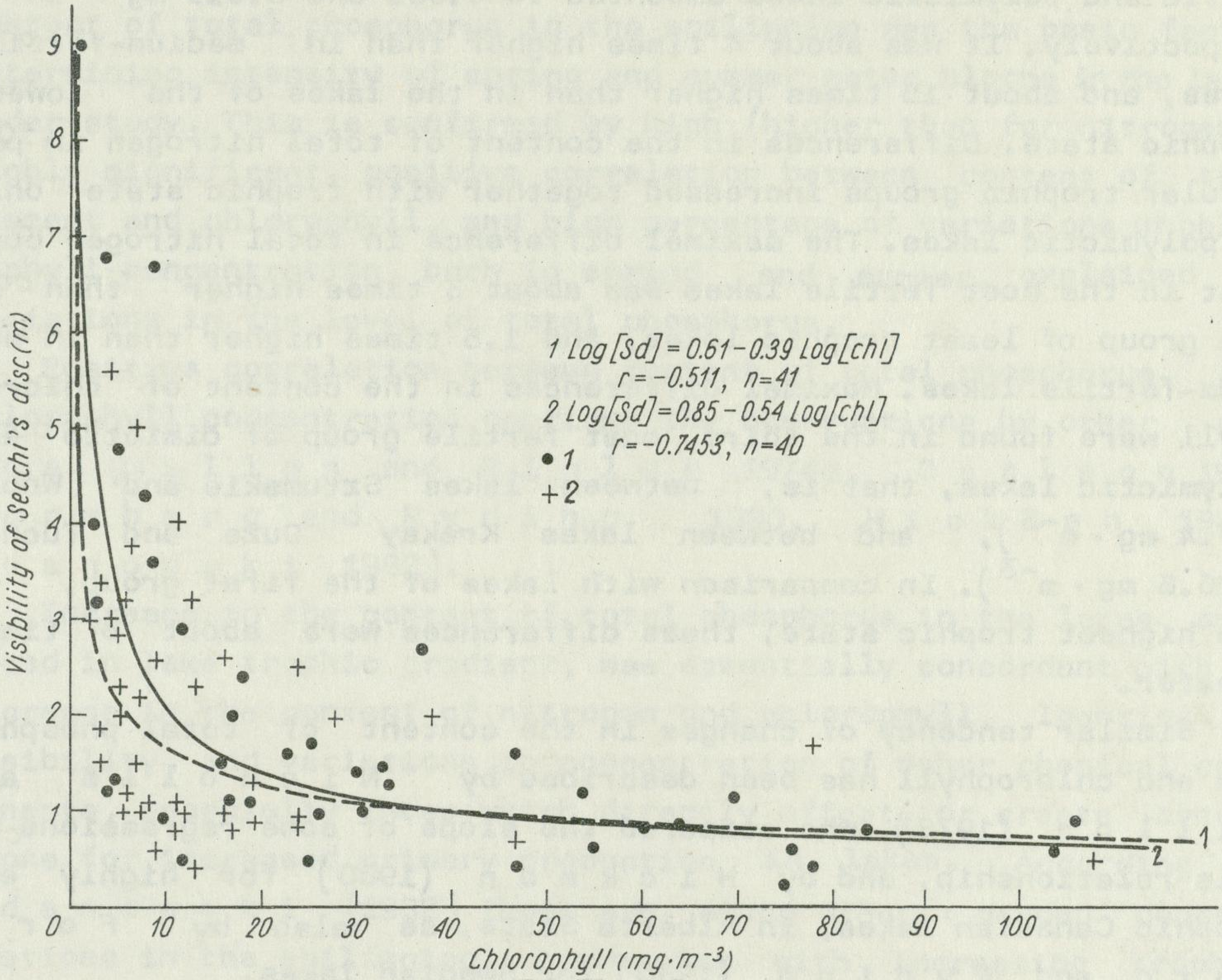

Fig. 2. Relationship between content of chlorophyll and visibility of Secchi's disc in the lakes under study, in spring (1) and summer (2)

towiec, Kołowin and Sędańskie, whereas in the remaining lakes it did not exceed 1.5 m. In summer, visibility in the polymictic lakes ranged from 0.2 and 1.6 m. The highest visibility was found only in two lakes: Burgale and Kołowin. Clear differences in visibility between spring and summer periods were recorded only for polymictic lakes with a low summer content of total phosphorus (<0.092 mg·dm^{-3}, Table II).

4. DISCUSSION

It was found that increasing lake trophic state and diversity as regards content of total phosphorus were accompanied by increasing differences in chlorophyll content between extreme lakes of the particular trophic groups. The greatest differences between maximum and minimum contents of total phosphorus were found in lakes of the highest trophic state. In summer, this difference for dimictic and polymictic lakes amounted to 0.331 and 0.619 mg $\cdot$ dm^{-3}, respectively. It was about 4 times higher than in medium-fertile lakes, and about 15 times higher than in the lakes of the lowest trophic state. Differences in the content of total nitrogen in particular trophic groups increased together with trophic state only in polymictic lakes. The maximal difference in total nitrogen content in the most fertile lakes was about 3 times higher than in the group of least trophic lakes, and 1.5 times higher than in medium-fertile lakes. Maximal differences in the content of chlorophyll were found in the third, most fertile group of dimictic and polymictic lakes, that is, between lakes Sztumskie and Wobel (87.4 mg $\cdot$ m^{-3}), and between lakes Kraksy Duże and Tuchel (226.6 mg $\cdot$ m^{-3}). In comparison with lakes of the first group, of the highest trophic state, these differences were about 8 times greater.

Similar tendency of changes in the content of total phosphorus and chlorophyll has been described by N i c h o l l s and D i l l o n (1978), who compared the slope of some regressions of this relationship, and by H i c k m a n (1980) for highly eutrophic Canadian lakes, in Alberta State, as also by F o r s-b e r g and R y d i n g (1980) for Swedish lakes.

On the other hand, visibility is most indicative of differences in the trophic state of less fertile lakes. In both mictic types and in both study periods variations in visibility decreased as the trophic state increased. In polymictic lakes, for instance, differences in visibility did not exceed 0.4 m.

The above comparison of changes in the content of phosphorus, nitrogen, chlorophyll and visibility indicates a varying information capacity of the indices discussed in assessing trophic state of individual lakes and their trophic groups. Scattering of the data, especially as regards concentrations of total phosphorus and chlorophyll, was most considerable in lakes of a high trophic state (dimictic lakes - group 3, polymictic lakes - group 2 and 3). This rules out the possibility of using a limited number of indices characterizing the trophic state of these lakes. Therefore, it is necessary to take into account other chemical and biological parameters. This seems to be particularly justified in case of polymictic lakes of the pond type, which may differ from each other in respect to biocoenotic structure and ways of functioning.

The results of the present studies generally showed that the content of total phosphorus in the epilimnion was the basic factor determining intensity of spring and summer water blooms in the lakes under study. This is confirmed by high (higher than for nitrogen), highly significant, positive correlation between content of this element and chlorophyll, and high percentage of variations of chlorophyll concentration, both in spring and summer, explained by variations in the level of total phosphorus.

Positive correlation between content of total phosphorus and chlorophyll concentration confirms the observations by other authors (Dillon and Rigler 1974a, Carlson 1977, Forsberg and Ryding 1980, Hickman 1980, Zdanowski 1982).

Increase in the content of total phosphorus in the lakes, analysed in lake trophic gradient, was essentially concordant with an increase in the content of nitrogen and chlorophyll, lowering of visibility, and variations in concentration of other chemical components, especially those which directly affect, or create conditions for increased primary production in lakes. According to Zdanowski (1982) these are, among others: oxygen concentrations in the epilimnion, increasing with increasing trophic state, water oxygenation, increasing levels of organic and phosphate phosphorus, ammonia, organic nitrogen, calcium, sodium, potassium, magnesium, chlorides, sulphates and carbonates, as well as water oxidability and electrolytic conductivity. Increasing lake trophic state is also accompanied by an increase in phytoplankton biomass and percentage of blue-green algae and nannoplankton in the biomass (Spodniewska 1983). However, the differences between spring and summer concentrations of particular chemical components in water were not the same in the dimictic lakes as in the polymictic lakes. This applies in particular to total phosphorus (Zdanowski 1983a, 1983b).

In dimictic lakes of the lowest and the highest trophic state, content of total phosphorus in the epilimnion was lower in summer than in spring. Summer levels of total nitrogen were higher, and so was the nitrogen to phosphorus ratio. Lower summer content of chlorophyll at higher visibility was noted only in the dimictic lakes of the first trophic group, i.e., of the lowest trophic state, that is, in water bodies for which lower summer content of total phosphorus in the epilimnion, and higher nitrogen to phosphorus ratio were found. Though summer decrease in the content of phosphorus did occur in the most fertile dimictic lakes, content of this element did not drop to a critical level which might have inhibited the growth of algae. Minimal content of total phosphorus amounted to 0.175 mg · dm^{-3}, and nitrogen to phosphorus ratio in these lakes continued to be low below 10.

In the polymictic lakes changes in the content of total phosphorus, total nitrogen, chlorophyll, and nitrogen to phosphorus ratio had a different tendency than in the dimictic lakes. Average summer content of total phosphorus in particular trophic groups was about twice as high as its spring level. Maximal increase of total phosphorus concentration (over 4-fold), from 0.082 to 0.357 mg·dm^{-3} was noted in Lake Tuchel. Summer concentration of chlorophyll in this lake reached the highest value ever recorded – 236.7 mg · m^{-3}.

Content of total nitrogen in the epilimnion of polymictic lakes was very similar in the analysed seasons. On the other hand, nitrogen to phosphorus ratio was lower in summer than in spring due to changes of total phosphorus concentration. The highest decrease in the N : P ratio was found in lakes of a low trophic state.

Comparison of changes in the content of total phosphorus in water and bottom sediments of the polymictic lakes indicated that in summer content of total phosphorus in water of these lakes increased as a result of its release from bottom sediments. The rate of phosphorus input from bottom sediments to water increased with increasing lake trophic state. The highest rate was found in the most fertile lakes (Z d a n o w s k i 1983b). It seems, therefore, that increase of summer concentration of total phosphorus in water is one of the more important factors accounting for higher summer concentration of chlorophyll and lower visibility in the polymictic lakes in relation to spring period and to dimictic lakes.

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5. SUMMARY

Measurements were made of visibility of Secchi's disc and of the spring and summer contents of chlorophyll in the epilimnion of

46 lakes. The lakes differed in their morphometry, trophic state and degree of anthropogenic impact (K a j a k and Z d a n o w s k i 1983). The results of studies are presented in Table I.

For spring period, significant positive correlation was found between content of total phosphorus in the epilimnion and chlorophyll (r = 0.514). There was no such correlation with total nitrogen (r = 0.258) and silicates (r = -0.045). Multiple correlation between concentration of chlorophyll and level of total phosphorus, total nitrogen and silicates was significant at the level of 0.01 (r = 0.515). The variables analysed account jointly for 26.6% of the variation of chlorophyll concentration, therein of total phosphorus - for 25.8%.

In summer, highly significant positive correlation was found between concentration of total phosphorus and content of chlorophyll (r = 0.756, Fig. 1), and less significant positive correlation between content of total nitrogen and chlorophyll (r = 0.493). There was no correlation with silicates (r = -0.103). Highly significant multiple correlation was also found between concentration of chlorophyll and content of total phosphorus, total nitrogen and silicates (r = 0.775) in summer. The variables analysed account jointly for 60.1% of the variation of chlorophyll concentration, therein of total phosphorus - for as much as 55.6%.

For spring and summer periods, highly significant negative correlation was found between concentration of chlorophyll and the visibility of Secchi's disc (Fig. 2).

When describing the trophic state of dimictic and polymictic lakes with respect to summer content of total phosphorus in the epilimnion, higher average spring content of total phosphorus was found in three trophic groups of these two mictic types (Table II). Similarly to summer concentration of total phosphorus, also average content of chlorophyll in spring and summer was higher. In spring, higher average content of total nitrogen was found only in the most fertile dimictic lakes, while in summer, and in case of polymictic lakes it changed in both periods in the same way as the average content of total phosphorus (Table II).

It was demonstrated that changes in the average content of total phosphorus and of total nitrogen in lakes of both mictic types and in both periods were accompanied by a decrease of the weight ratio of nitrogen to phosphorus (Table II).

In spring and summer, visibility decreased as the trophic state increased mainly in the dimictic lakes, while in the polymictic lakes it was clearly higher in the group of lakes of the highest trophic state (Table II).

The present study has confirmed the observations reported by Z d a n o w s k i (1983b) that an increase in the content of total phosphorus in the epilimnion of polymictic lakes was the result of its inputs from bottom sediments, and to a less extent of higher summer concentration of chlorophyll and lower visibility in these lakes.

6. POLISH SUMMARY

Przeprowadzono pomiary widzialności krążka Secchi'ego i zawartości chlorofilu w okresie wiosennym i letnim w epilimnionie 46 jezior. Jeziora różniły się morfometrią, trofią i stopniem antropogennego zagrożenia (K a j a k i Z d a n o w s k i 1983). Wyniki badań przedstawiono w tab. I.

Stwierdzono dla okresu wiosennego istotną dodatnią zależność w badanych jeziorach między zawartością fosforu ogólnego w epilimnionie i chlorofilem (r = 0,514) oraz brak zależności dla azotu ogólnego (r = 0,258) i krzemianów (r = -0.045). Korelacja wielokrotna między stężeniem chlorofilu a stężeniem fosforu ogólnego, azotu ogólnego i krzemianów jest dodatnio istotna na poziomie 0,01 (r = 0,515). Analizowane zmienne wyjaśniają w sumie 26,6% zmienności stężeń chlorofilu, z czego fosfor ogólny - 25,8%.

W okresie letnim stwierdzono wysoce istotną dodatnią zależność między stężeniem fosforu ogólnego i stężeniem chlorofilu (r = 0,756, rys. 1), słabszą zależność dodatnią między zawartością azotu ogólnego i chlorofilem (r = 0.493) i brak zależności dla krzemianów (r = -0,103). Wykazano także dla tego okresu wysoce istotną zależność wielokrotną między stężeniem chlorofilu i zawartością fosforu ogólnego, azotu ogólnego i krzemianów (r = 0,775). Analizowane zmienne wyjaśniają w sumie 60,1% zmienności stężeń chlorofilu, z czego fosfor ogólny - aż 55,6%.

Dla okresu wiosennego i letniego stwierdzono wysoce istotną ujemną zależność między koncentracją chlorofilu i widzialnością krążka Secchi'ego (rys. 2).

Charakteryzując trofię jezior dymiktycznych i polimiktycznych pod względem letniej zawartości fosforu ogólnego w epilimnionie stwierdzono wzrost średniej wiosennej zawartości fosforu ogólnego w 3 grupach troficznych tych 2 typów miktycznych (tab. II). Analogicznie do letniego stężenia fosforu ogólnego wzrasta także średnia zawartość chlorofilu wiosną i latem. Średnia zawartość azotu ogólnego jest wyższa w okresie wiosennym jedynie w najżyźniejszych jeziorach dymiktycznych, podczas gdy dla okresu letniego, a w jeziorach polimiktycznych dla obu okresów, zmienia się ona analogicznie do zmian średniej zawartości fosforu ogólnego (tab. II).

Wykazano, że zmianom średniej zawartości fosforu ogólnego i azotu ogólnego towarzyszy w obu grupach miktycznych i analizowanych okresach obniżenie stosunku wagowego azotu do fosforu (tab. II).

Widzialność obniża się wiosną i latem wraz ze wzrostem trofii głównie w jeziorach dymiktycznych, a w jeziorach polimiktycznych jest ona wyraźnie wyższa w grupie jezior o najwyższej trofii (tab. II).

Potwierdzono obserwacje Zdanowskiego (1983b), że wzrost zawartości fosforu ogólnego w epilimnionie jezior polimiktycznych jest konsekwencją jego dopływu z osadów dennych i dalej - wyższej koncentracji letniej chlorofilu i niższej widzialności.

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