EKOLOGIA POLSKA (Ekol. pol.)	31	2	309–331	1983

Bogusław ZDANOWSKI

Department of Hydrobiology, Inland Fisheries Institute,
Building 5, 10-957 Olsztyn-Kortowo, Poland

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

IV. CHEMISTRY OF BOTTOM SEDIMENTS IN 37 LAKES *

ABSTRACT: The content of total phosphorus and total nitrogen in the near-bottom water layer was found to increase with the rising trophic state of dimictic lakes. The content of total organic and mineral phosphorus, organic nitrogen and organic matter in the sediments was highest in dimictic lakes of the lowest and highest trophic states. In polymictic lakes, the content of total phosphorus and total nitrogen in the water, and the content of total, mineral and organic phosphorus as well as of organic matter in the sediments increased with the rising trophic state of the lakes.

KEY WORDS: Lakes, trophic state, dimictic lakes, polymictic lakes, bottom sediments, phosphorus, nitrogen, organic matter, seasonal changes.

Contents

* Pracę wykonano w ramach Programu Rządowego PR-4 („Optymalizacja produkcji i spożycia białka").

1. Introduction

An important process determining changes in the content of nutrients in the epilimnion in summer is their supply from bottom sediments. Investigations carried out by K a j a k et al. (1975) in the Mikołajskie Lake indicate that between ten and twenty per cent of the organic matter produced in a water body in deposited for good in the bottom sediments. In summer, the sedimentation of organic matter in this lake made over 50% of total production. These findings indicate the intensive mineralization and release from bottom sediments.

In the Rybinsk Reservoir about 35% of the sedimented nitrogen is released from the bottom sediments into the water (T r i f o n o v a 1974). Studies of Lake Ontario (K e m p and M u d r e c h o v a 1972) have shown that at least 20% of the organic nitrogen contained in the bottom sediments returns to the lake from the 6-cm top layer. In the top sediment layer, organic nitrogen constituted about 90% of the content of total nitrogen.

The amounts of phosphorus released from the bottom sediments may be considerable, from several to between ten and twenty $mg \cdot m^{-2}$ (K a j a k 1979). If there are favourable atmospheric and mictic conditions, these quantities may lead to an intensive inner enrichment of the lakes, providing the basic source of this element for the production zone of lakes. This applies in particular to shallow, strongly mixed polymictic lakes, and stratified water bodies with large littoral and sublittoral zones (P a t a l a s 1960, F e e 1979).

Comparisons of the content of total phosphorus and nitrogen in the water, macrophytes, fish and bottom sediments of some lakes show that about 90% of these elements is contained in the surface layer of the bottom sediments (K a j a k 1976, 1979, H i l l-b r i c h t - I l k o w s k a and Z d a n o w s k i - in press). As the content of phosphorus and nitrogen in the sediments is so high, relative to other elements of the ecosystem, it may be presumed that even the release of several per cent of them from the sediments may cause clear changes in their content in the water.

The present paper presents selected results from studies of the chemistry of the sediments of 37 lakes located in north-eastern Poland. Assessments were made of changes in the content of organic matter, total, organic and mineral phosphorus, and of organic nitrogen in the top sediment layer[1]. Changes in the content of phosphorus and nitrogen in the sediments were compared with changes in the concentration of these elements in the near-bottom water layer.

2. MATERIAL AND METHODS

The chemistry of bottom sediments was studied in 37 lakes, in 1977 and 1978 (Table I). A description of their morphometry and trophic state, as well as of the degree of their pollution can be found in the paper of K a j a k and Z d a n o w s k i (1983). The chemical composition of the water has been described by Z d a n o w s k i (1983).

On each lake bottom sediment samples were collected twice: in the spring (April-May) and in the summer (August). The samples were collected with a 50 cm^2 tubular sampler (K a j a k, K a c p r z a k and P o l k o w s k i 1965). In the deepest part of each lake 3-5 samples were collected.

The content of organic matter was determined as the loss after ashing the sediment at 550°C, and after partial carbonate regeneration by adding distilled water saturated with carbon dioxide to the ashed sediment, whereafter the water was evaporated and the samples dried up at 105°C to a constant weight (S t a n g e n b e r g 1938).

[1]The chemical composition of bottom sediments: the content of P, N, Ca, K, Na, Mg, Mn, organic matter and silica in the 0-15 cm layer of bottom sediments, of the lakes under study are being elaborated (B. Zdanowski, B. Samulowska-Dramińska - in preparation).

Table I. Values of the parameters studied in tne near-bottom water period, in dimictic (d)

No.	Lakes	Depth max. (and average) m	Spring: water of near-bottom layers: Tot-P	Tot-N	Spring: bottom sediments: organic matter	Tot-P	Tot_{org}-P	Tot_{min}-P
			mg · dm^{-3}		per cent of dry weight			
1	Barlewickie (p)	8.5 (4.2)	0.840	1.91	40.3	0.58	0.39	0.19
2	Będze (p)	6.7 (2.8)	0.155	1.76	60.6	0.35	0.28	0.08
3	Brajnickie (p)	5.2 (2.7)	0.087	1.91	44.7	0.39	0.27	0.12
4	Burgale (p)	7.4 (4.6)	0.033	1.76	22.9	0.12	0.08	0.04
5	Czos (d)	42.6 (11.1)	0.097	0.98	21.5	0.21	0.10	0.11
6	Długie near Szczytno (p)	5.0 (2.8)	0.243	-	47.3	0.47	0.32	0.15
7	Ełckie (d)	55.8 (15.0)	0.140	1.16	37.4	0.23	0.14	0.09
8	Gim (d)	25.8 (7.6)	0.044	0.86	74.2	0.38	0.30	0.08
9	Hartowiec (p)	5.2 (2.8)	0.061	0.72	36.1	0.26	0.18	0.08
10	Iławskie (p)	2.8 (1.1)	0.238	2.36	42.9	0.18	0.12	0.06
11	Juno Północne (d)	33.0 (11.9)	0.420	1.96	30.8	0.64	0.29	0.35
12	Juno Południowe (d)		0.510	1.80	36.7	0.33	0.20	0.12
13	Kierzlińskie (d)	44.5 (11.7)	0.099	0.70	22.2	0.33	0.14	0.19
14	Kokowo (d)	11.7 (3.3)	0.104	1.06	15.0	0.39	0.28	0.11
15	Kołowin (p)	7.2 (4.0)	0.054	1.26	54.4	0.22	0.08	0.13
16	Kraksy Duże (p)	4.0 (1.1)	0.324	2.66	43.2	0.50	0.33	0.17
17	Kuc (d)	28.0 (8.0)	0.034	0.76	42.6	0.24	0.17	0.08
18	Lampackie (d)	38.5 (11.1)	0.065	1.78	30.4	0.28	0.13	0.15
19	Liwieniec (p)	2.4 (1.2)	0.116	1.81	36.7	0.32	0.22	0.10
20	Małszewo (d)	16.9 (6.3)	0.058	1.40	24.8	0.24	0.12	0.12
21	Mój (p)	4.1 (2.4)	0.042	4.96	52.8	0.25	0.20	0.05
22	Ołów (d)	40.1 (12.9)	0.080	2.80	42.5	0.30	0.19	0.11
23	Piłakno (d)	56.6 (13.0)	0.068	0.56	49.4	1.28	0.70	0.59
24	Probarskie (d)	31.0 (9.2)	0.036	0.70	47.0	1.15	0.46	0.70
25	Rańskie (p)	7.8 (3.8)	0.056	2.26	31.3	0.16	0.09	0.07
26	Rzeckie (d)	29.0 (6.9)	0.183	-	38.4	0.37	0.21	0.15
27	Sambród (p)	4.3 (1.9)	0.097	1.11	36.8	0.24	0.17	0.07
28	Sarż (d)	15.0 (5.0)	0.051	1.25	41.5	0.26	0.19	0.06
29	Sasek Mały (p)	3.7 (1.6)	0.215	1.81	33.7	0.19	0.12	0.08
30	Sędańskie (p)	6.1 (2.5)	0.080	1.06	-	0.21	0.14	0.07
31	Siercze (p)	2.0 (1.0)	0.056	1.16	-	0.24	0.14	0.10
32	Skanda (d)	12.0 (5.8)	0.075	0.73	32.1	0.34	0.21	0.13
33	Stryjewskie (p)	6.2 (2.6)	0.060	1.66	47.8	0.15	0.09	0.06
34	Sztumskie (d)	24.0 (6.0)	0.728	1.61	33.6	0.22	0.10	0.12
35	Tuchel (p)	5.1 (2.7)	0.067	1.06	-	0.29	0.21	0.08
36	Warpuńskie (p)	6.9 (2.6)	0.067	1.46	28.9	0.17	0.12	0.06
37	Wobel (d)	15.0 (4.2)	0.935	3.16	35.8	0.89	0.41	0.48

*Oxygen content measured at the depth of 30 m.

layer and in the bottom sediments (0-2 cm), in spring and summer and polymictic (p) lakes

Summer										
water of near-bottom layers					bottom sediments					
Tot_{org}-N	Tot-P	Tot-N	Tot-Fe	O_2	pH	organic matter	Tot-P	Tpt_{org}-P	Tot_{min}-P	Tot_{org}-N
mg • dm^{-3}						per cent of dry weight				
1.53	0.980	4.41	0.00	6.0	8.2	43.7	0.57	0.37	0.20	1.42
2.10	0.170	2.36	0.00	9.4	7.8	54.1	0.24	0.19	0.05	2.13
1.40	0.126	1.86	0.00	12.4	7.4	45.8	0.29	0.20	0.08	1.56
1.07	0.058	1.21	0.00	8.8	7.8	23.8	0.12	0.09	0.03	0.96
0.84	0.265	1.30	0.00	0.0	7.8	22.0	0.28	0.17	0.11	0.80
1.54	0.337	1.81	0.00	7.9	7.6	46.8	0.33	0.24	0.09	1.45
1.19	0.277	1.56	0.03	0.0*	7.2	28.5	0.25	0.17	0.08	0.97
2.03	0.050	1.10	0.00	0.0	7.2	73.5	0.26	0.20	0.06	-
1.00	0.215	1.51	0.00	9.4	8.0	-	0.25	0.18	0.08	1.08
1.44	0.447	3.66	0.07	12.7	7.7	49.2	0.57	0.48	0.09	1.75
1.03	0.997	3.70	0.18	0.1*	7.1	32.2	0.48	0.27	0.20	1.07
1.07	0.795	3.55	0.11	0.0	7.2	42.00	0.50	0.30	0.19	1.19
0.64	0.106	0.78	0.00	2.8*	7.5	21.8	0.31	0.09	0.22	0.76
0.83	0.222	2.01	0.91	0.6	7.4	9.5	0.30	0.11	0.19	0.68
1.47	0.061	0.71	0.02	9.4	8.2	-	0.23	0.18	0.05	1.91
1.35	0.535	3.46	0.30	1.4	7.9	37.8	0.31	0.18	0.14	0.97
1.52	0.037	0.47	0.00	2.9	7.4	47.9	0.18	0.13	0.05	1.53
0.85	0.176	0.82	0.13	0.0	7.7	29.2	0.15	0.06	0.08	0.68
1.38	0.321	1.76	0.00	10.4	8.6	21.2	0.36	0.21	0.15	1.18
0.74	0.071	1.55	0.11	0.0	7.2	20.1	0.18	0.10	0.08	1.31
1.57	0.056	1.31	0.00	7.6	8.0	46.6	0.15	0.11	0.05	1.75
1.20	0.176	1.55	0.00	0.0*	7.3	45.9	0.23	0.16	0.07	1.08
1.88	0.074	1.40	0.00	3.1*	7.5	45.6	0.87	0.43	0.44	1.67
1.52	0.065	0.48	0.04	0.5	6.5	45.4	1.11	0.88	0.23	1.10
1.60	0.141	0.64	0.00	6.5	7.8	31.4	0.15	0.08	0.06	1.17
0.97	0.124	1.60	0.20	0.0*	7.5	36.6	0.54	0.28	0.26	1.14
1.30	0.157	2.16	0.07	14.0	8.8	34.0	0.18	0.13	0.05	1.38
2.36	0.165	1.35	1.08	0.0	6.8	39.6	0.24	0.21	0.03	1.31
1.18	0.305	3.76	0.47	-	8.2	32.0	0.29	0.20	0.09	1.68
-	0.079	1.56	0.18	7.5	8.3	34.6	0.15	0.08	0.07	1.00
-	0.062	1.11	0.02	7.1	8.0	56.9	0.19	0.13	0.06	1.70
0.96	0.087	2.10	0.19	0.0	7.0	29.9	0.25	0.16	0.09	0.85
1.34	0.140	1.66	0.15	8.4	7.6	46.7	0.15	0.09	0.05	1.33
1.01	1.197	2.61	0.00	0.0	7.2	33.9	0.34	0.19	0.15	1.37
-	0.351	1.41	0.06	0.3	8.2	25.2	0.14	0.07	0.08	0.86
1.27	0.198	1.11	0.08	6.9	8.5	22.6	0.17	0.12	0.06	0.97
1.50	0.930	8.56	0.13	0.0	6.3	30.0	0.93	0.48	0.45	1.92

Organic nitrogen was determined by Kjeldahl's method in air-dried sediment samples. The analysis was done on an "ORION" Model 407 ion-analyser by using a selective ammonium electrode.

Total organic and mineral phosphorus was determined according to the method described by G o l a c h o w s k a (1977). After being weighed the sediment was subjected to a two-staged, acid and alkaline, extraction.

Mineral phosphorus was extracted by treating sediment samples with 1 n sulphuric acid containing an addition of NH_4F, shaking and centrifugation. The acid extraction was repeated three times. Organic phosphorus was extracted in sediment samples, after the acid extraction, by treating them with 2 n NaOH, heating in the water bath at 90°C for 30 minutes, and then centrifugating. This procedure was repeated three times.

Total mineral phosphorus, bound in compounds with iron, aluminium and calcium, constitutes the sum of phosphorus determined in the acid and alkaline extraction, determined in the latter by its pretreatment with 5 n sulphuric acid and filtration of the samples.

Total phosphorus was determined by burning of equal proportions of the acid and alkaline extraction in a mixture of 10 n sulphuric and perchloric acids until the appearance of a thick white smoke. Organic phosphorus represents the difference between the concentration of total phosphorus and mineral phosphorus.

The results (Table I) have been analysed separately for dimictic and polymictic lakes. Three lake groups differing in the trophic state have been separated, for each of the mictic types. The trophic state of the lakes has been characterized on the basis of the summer concentration of total phosphorus in the epilimnion (Z d a n o w s k i 1983). Dimictic lakes had the following summer levels of total phosphorus: Group 1 - 0.020-0.044 mg · dm^{-3} (lakes Gim, Kierzlińskie, Kuc, Ołów, Piłakno, Probarskie, Sarż, Skanda), Group 2 - 0.059-0.147 mg · dm^{-3} (lakes Czos, Kokowo, Lampackie, Małszewo, Rzeckie), and Group 3 - 0.175-0.506 mg · dm^{-3} (lakes Ełckie, Juno Północne, Juno Południowe, Sztumskie, Wobel) and polymictic lakes: Group 1 - 0.054-0.092 mg · dm^{-3} (lakes Burgale, Kołowin, Mój, Rańskie, Sędańskie, Siercze), Group 2 - 0.134-0.285 mg · dm^{-3} (lakes Bądze, Brajnickie, Długie, Hartowiec, Sambród, Sasek Mały, Stryjewskie, Warpuńskie), and Group 3 - 0.321-0.940 mg · dm^{-3} (lakes Barlewickie, Iławskie, Kraksy Duże, Liwieniec, Tuchel).

3. RESULTS

3.1. Changes of organic matter in bottom sediments

The content of organic matter in the bottom sediments of the dimictic and polymictic lakes ranged from 15.0 to 74.2% and 23.0 to 60.6% in spring, and from 9.5 to 73.5% and 21.2 to 56.9% d. wt, respectively, in summer (Table II). Its average concentration was higher in the polymictic lakes (39.9% d. wt) than in the dimictic lakes (33.6% d. wt).

The content of organic matter in the sediments of dimictic lakes is slightly lower in summer than in spring, on an average by 4%, and in polymictic lakes - by 7%.

Among the dimictic lakes under study the highest spring content of organic matter was found in lakes of the lowest trophic state and with very stable thermal conditions in summer, i.e., lakes Sarż, Ołów, Gim, Piłakno, Probarskie and Kuc (41.4-74.2% d. wt), and among the polymictic lakes - in lakes Długie, Mój, Stryjewskie, Kołowin and Bądze (47.3-60.9% d. wt). In the remaining dimictic lakes the content of organic matter in the sediments was found to be lower.

The content of organic matter in the sediments increased only slightly with the rising trophic state; it was lower in summer than in spring. This difference was more pronounced in lakes with a high trophic state (Table II).

3.2. Changes of phosphorus in bottom sediments and near-bottom water layer

In spring, the content of total phosphorus in the bottom sediments of the dimictic lakes ranged from 0.2 to 1.3%, and in summer from 0.2 to 1.1% d. wt. Its concentrations in the sediments of the polymictic lakes appeared to be lower, varying between 0.1 and 0.5% in spring, and between 0.1 and 0.6% d. wt in summer (Table II).

Table II. The mean and the range of variation of pH, contents of oxygen, total phosphorus and total phosphorus, mineral phosphorus and organic nitrogen in the 0-2 cm layer of bottom sediments, in pect of the summer content of to-

Lakes	Trophic group of lakes	Tot-P in epilimnion in summer (mg dm^{-3})	Spring: water of near-bottom layers: Tot-P	Spring: water of near-bottom layers: Tot-N	Spring: bottom sediments: organic matter	Spring: bottom sediments: Tot-P	Spring: bottom sediments: Tot$_{org}$-P	Spring: bottom sediments: Tot$_{min}$-P
		mg · dm^{-3}			per cent of dry weight			
Dimictic	1	0.036	0.061	1.17	43.9	0.54	0.29	0.23
		0.020-0.044	0.036-0.099	0.70-2.80	22.2-74.2	0.26-1.28	0.17-0.70	0.07-0.70
	2	0.091	0.101	1.30	26.0	0.30	0.17	0.13
		0.059-0.147	0.058-0.183	0.98-1.78	15.0-38.4	0.21-0.39	0.10-0.28	0.11-0.15
	3	0.309	0.547	1.94	34.9	0.46	0.23	0.23
		0.175-0.506	0.140-0.935	1.16-3.16	30.8-37.4	0.23-0.89	0.10-0.41	0.09-0.48
Polymictic	1	0.079	0.053	2.08	40.4	0.20	0.12	0.08
		0.054-0.092	0.033-0.080	1.06-4.96	23.0-54.4	0.12-0.25	0.08-0.20	0.04-0.13
	2	0.169	0.123	1.49	42.0	0.28	0.19	0.09
		0.134-0.285	0.060-0.243	0.72-1.91	28.9-60.6	0.15-0.47	0.09-0.32	0.06-0.15
	3	0.526	0.317	1.96	42.5	0.38	0.25	0.12
		0.321-0.940	0.067-0.840	1.06-2.36	36.7-50.0	0.18-0.50	0.12-0.39	0.06-0.19

nitrogen in the near-bottom water layer, and content of organic matter, total phosphorus, organic spring and summer, in dimictic and polymictic lakes, and in their trophic groups differing in res- tal phosphorus in the epilimnion

Summer									
water of near-bottom layers					bottom sediments				
Tot_{org}-N	Tot-P	Tot-N	pH	O_2	organic matter	Tot-P	Tot_{org}-P	Tot_{min}-P	Tot_{org}-N
$mg \cdot dm^{-3}$				$mg \cdot dm^{-3}$	per cent of dry weight				
1.51	0.095	1.15	7.3		43.7	0.43	0.28	0.15	1.19
0.64-2.36	0.050-0.176	0.66-2.1	6.5-,7.5	0.0-3.1	21.8-73.5	0.17-1.11	0.09-0.88	0.03-0.42	0.76-1.60
0.84	0.172	1.46	7.6	0.0	23.5	0.29	0.14	0.15	0.92
0.74-0.83	0.071-0.265	0.82-2.01	7.2-7.9		9.5-36.6	0.15-0.54	0.06-0.28	0.08-0.26	0.68-1.31
1.16	0.839	4.00	7.0	0.0	33.3	0.50	0.27	0.21	1.31
1.01-1.50	0.277-1.197	1.56-8.56	6.3-7.2		28.5-42.0	0.16-0.93	0.05-0.48	0.08-0.45	0.97-1.92
1.43	0.076	1.09	8.0	7.8	38.7	0.16	0.11	0.05	1.41
1.06-1.57	0.056-0.141	0.64-1.56	7.8-8.3	6.5-9.4	23.8-56.9	0.12-0.23	0.08-0.18	0.03-0.07	0.96-1.91
1.39	0.206	2.03	8.0	9.8	40.5	0.24	0.17	0.07	1.45
1.00-2.08	0.126-0.337	1.11-3.76	7.4-8.8	6.9-14.0	22.6-54.1	0.15-0.33	0.09-0.24	0.05-0.09	0.97-2.13
1.42	0.527	2.94	7.9	6.0	35.5	0.39	0.26	0.13	1.23
1.35-1.53	0.321-0.980	1.41-3.66	7.2-8.2	0.3-12.7	21.2-49.2	0.14-0.57	0.07-0.48	0.08-0.20	0.85-1.75

The highest concentrations of total organic and mineral phosphorus in the bottom sediments of the dimictic lakes have been recorded for lakes Piłakno, Probarskie, Ełckie, Juno Północne, Juno Południowe, Sztumskie and Wobel. In the other lakes of this group the differences in the content of total phosphorus in the bottom sediments were small.

In the polymictic lakes, a rise of the trophic state is accompanied by a steady increase in the content of total phosphorus. In lakes of groups 1 and 2 its content is lower in summer than in spring (Table II). The decrease in the content of total and organic phosphorus in the sediments of these lakes corresponds with the increase in the concentration of total phosphorus in the near-bottom water layer (Table II).

As the concentration of total phosphorus increases, the content of organic phosphorus in the sediments of dimictic lakes grows (Fig. 1). The highest content of organic phosphorus has been recorded for lakes characterized by a high concentration of total phosphorus in the sediments, that is in lakes of a high (Juno Północne, Juno Południowe, Wobel) and those with a low (Piłakno, Probarskie) trophic state. The proportion of organic phosphorus in total phosphorus varied between 39 and 79% in spring, and 29 and 88% in summer. The average content of the organic fraction of phosphorus at this time is similar and amounts to 56%.

A comparison of the content of total and organic phosphorus in the sediments, and in the surface and near-bottom water layers of the dimictic lakes shows that there is no direct relationship in the spring between the fertility of the water and bottom sediments in respect of the content of phosphorus (Fig. 1). An exception is the fertile lakes Ełckie, Juno Południowe, Rzeckie, Sztumskie and Wobel in which a simultaneous accumulation is observed in phosphorus of the water and of the sediments. A high-rate accumulation of phosphorus in the bottom sediments, with lower variations in the level of phosphorus in the water, is found in lakes Piłakno and Probarskie (Fig. 1).

In summer, an increase of total phosphorus relative to the spring period, is observed in the following dimictic lakes: Czos, Ełckie, Juno Południowe, Rzeckie, Sztumskie and Wobel (Fig. 1). In the remaining dimictic lakes the content of total phosphorus in the bottom sediments is lower in summer than in spring, with a si-

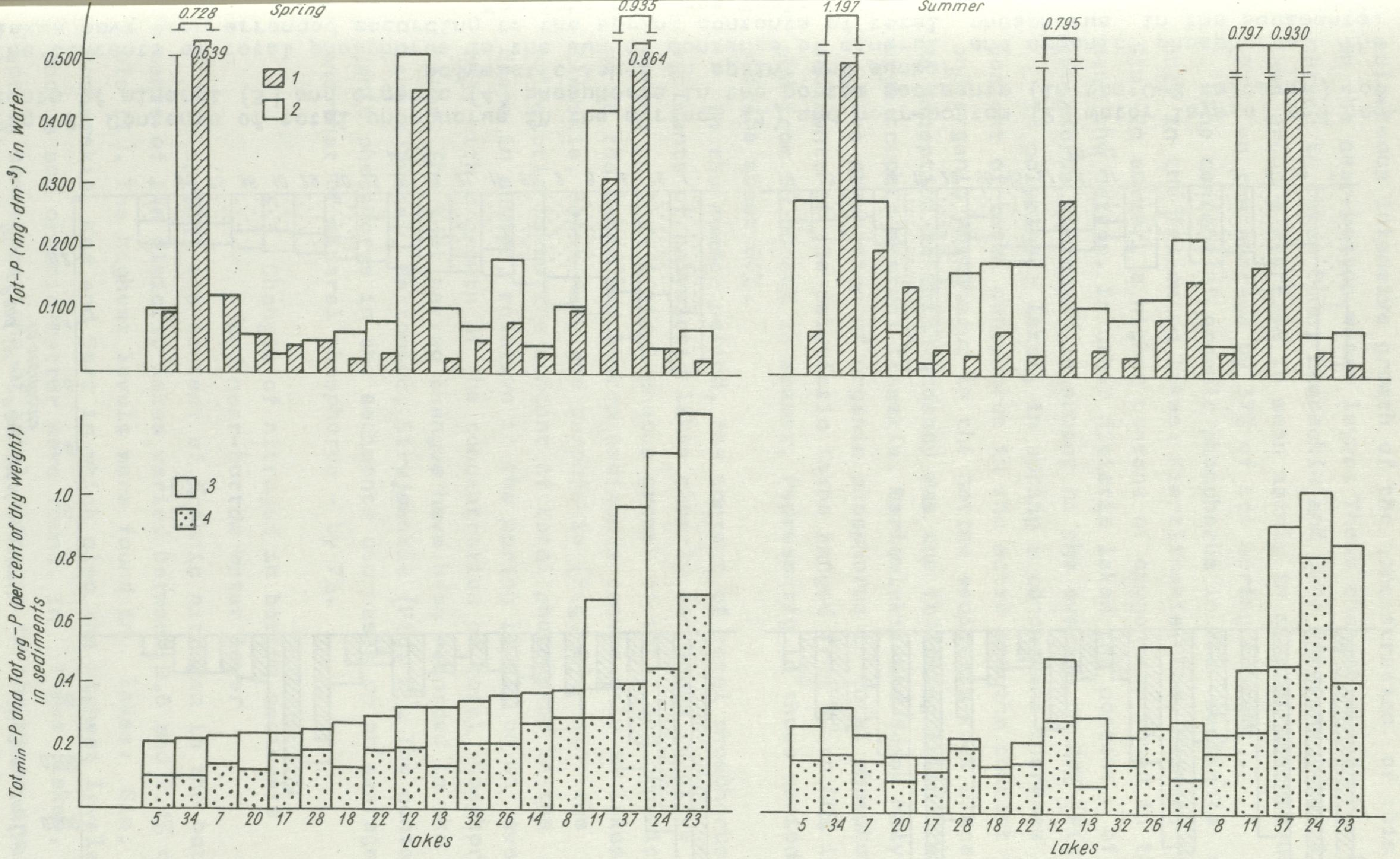

Fig. 1. Contents of total phosphorus in the surface (1) and near-bottom (2) water layer, and contents of mineral (3) and organic (4) phosphorus in the bottom sediments (in the 0–2 cm layer) of dimictic lakes in spring and summer
The contents of total phosphorus is the sum of contents of mineral and organic phosphorus. The lakes have been arranged according to the spring content of total phosphorus in the sediments. For lake nos. see Table I

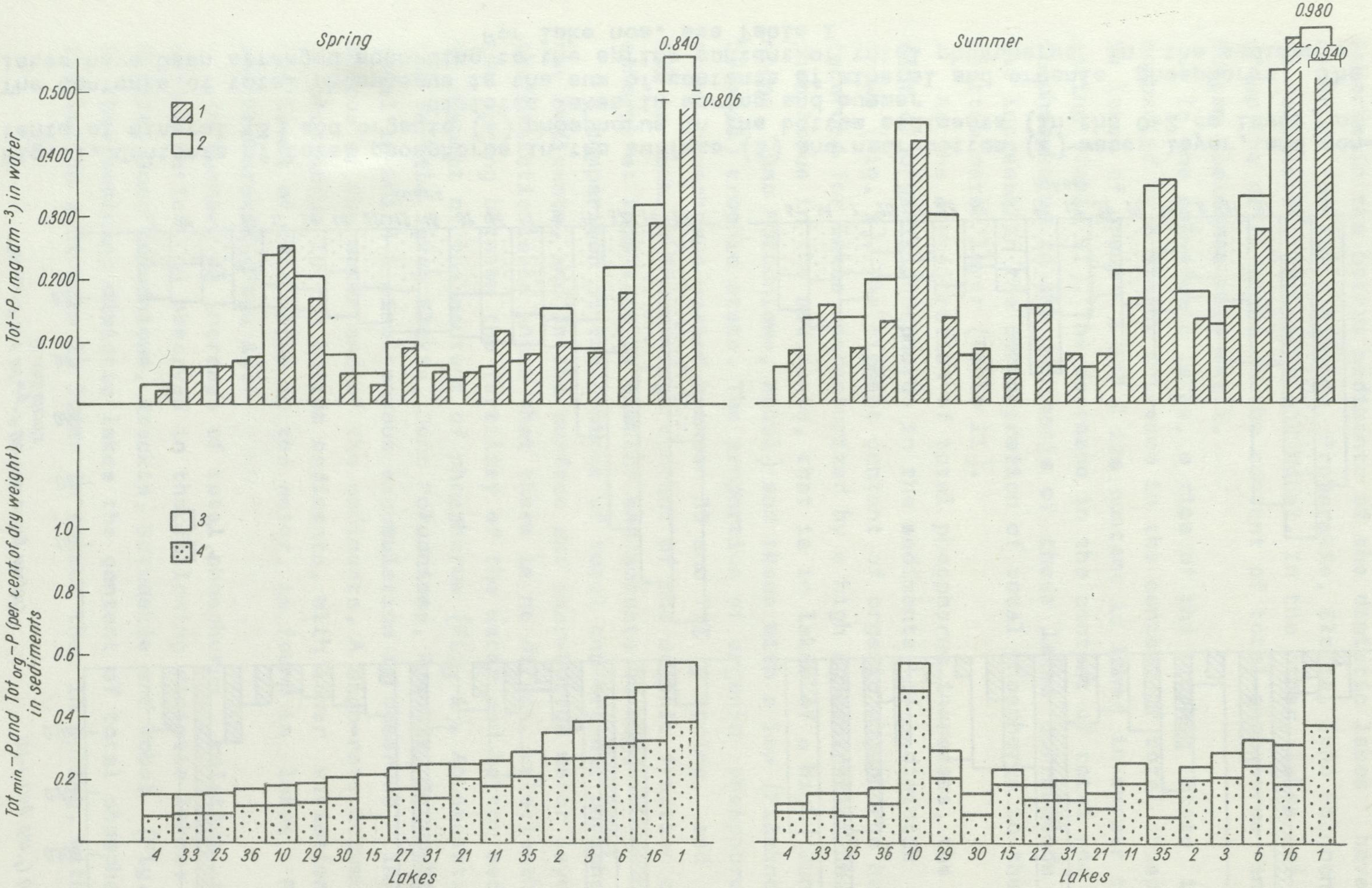

Fig. 2. Contents of total phosphorus in the surface (1) and near-bottom (2) water layers, and contents of mineral (3) and organic (4) phosphorus in the bottom sediments (in the 0-2 cm layer) of polymictic lakes in spring and summer

The contents of total phosphorus is the sum of contents of mineral and organic phosphorus. The lakes have been arranged according to the spring contents of total phosphorus in the sediments. For lake nos. see Table I multaneous intensive growth of the concentration of this element in the near-bottom water layer. These changes appear to be most marked in lakes Ołów, Lampackie and Juno Północne (Fig. 1). In this lake group a decrease is seen mainly in mineral phosphorus (by 7--77%, on the average by 37% of its spring content).

The content of organic phosphorus in the sediments decreased only in the following lakes: Kierzlińskie, Kuc, Skanda, Piłakno and Gim. In summer, a higher content of oxygen was found in these lakes near the bottom. In other dimictic lakes the content of organic phosphorus increased in summer on the average by 28% (Fig. 1).

In polymictic lakes, in spring a concordant increase of the content of total phosphorus in the water and the content of total and organic phosphorus in the bottom sediments took place (Fig. 2). An exception to this tendency was the following lakes with very high trophic status: Iławskie, Barlewickie and Sasek Mały.

The proportion of organic phosphorus in total phosphorus in the sediments of the polymictic lakes ranged from 39 to 80% in spring, and from 56 to 84% in summer, representig in these periods on an average about 66%.

In the summer period, the content of total phosphorus in the sediments of polymictic lakes clearly decreases relative to the spring period. A simultaneous growth of total and organic phosphorus in the water and bottom sediments occurs only in lakes Kołowin, Iławskie, Sasek Mały and Warpuńskie (Fig. 2). In the remaining polymictic lakes the content of total phosphorus in the sediments drops in summer, relative to the spring level, on an average by 23%, with a growth of the concentration of total phosphorus in the water. The most marked changes have been recorded in the following lakes: Tuchel, Hartowiec, Stryjewskie (Fig. 2). The content of organic phosphorus in the sediments decreases on an average by 26%, and that of mineral phosphorus - by 7%.

3.3. Changes of nitrogen in bottom sediments and near-bottom water layer

In spring, the content of organic nitrogen in the bottom sediments of the dimictic lakes varied between 0.6 and 2.4% d. wt (Table II). The highest levels were found in lakes: Gim, Piłakno, Probarskie, Kuc and Sarż in which also the highest levels of phosphorus and organic matter were found. In these lakes, lowered spring concentrations of total nitrogen in the water are accompa-

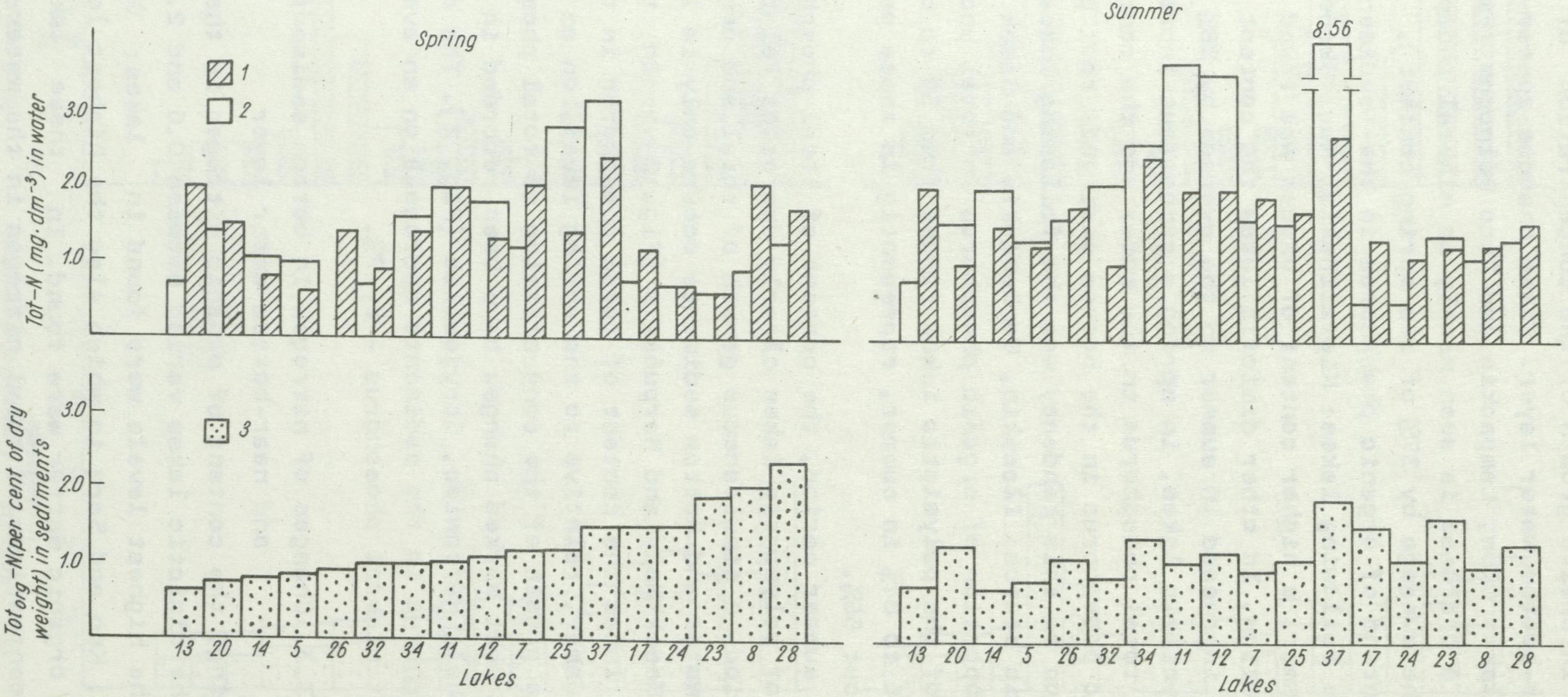

Fig. 3. Contents of total nitrogen in the surface (1) and near-bottom (2) water layers, and contents of organic nitrogen (3) in the bottom sediments of dimictic lakes in spring and summer The lakes have been arranged according to the spring contents of organic nitrogen in the sediments. For lake nos. see Table I

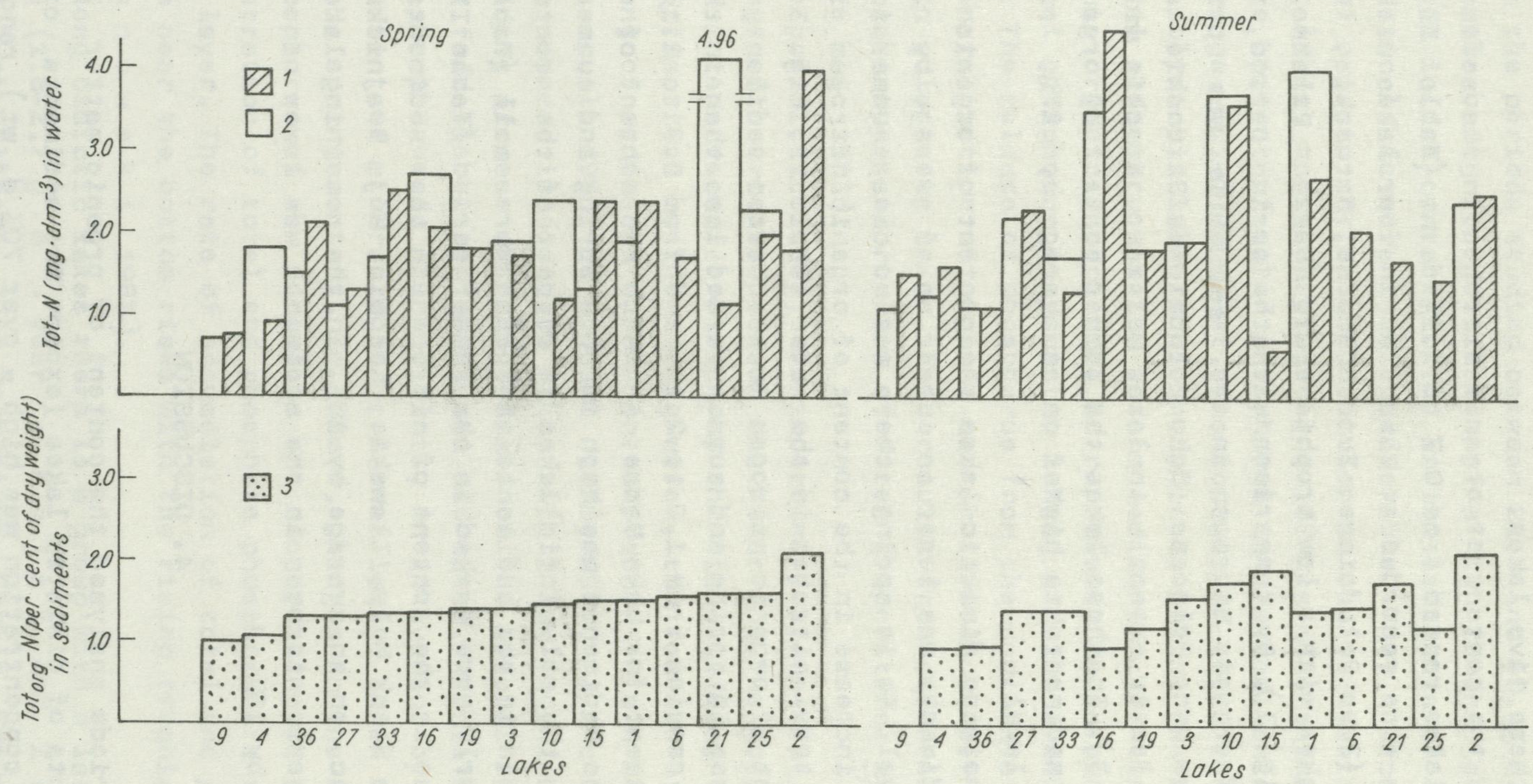

Fig. 4. Contents of total nitrogen in the surface (1) and near-bottom (2) water layers, and contents of organic nitrogen (3) in the bottom sediments of polymictic lakes in spring and summer The lakes have been arranged according to the spring content of organic nitrogen in the sediments. For lake nos. see Table I

nied by high levels of organic nitrogen in the sediments (Fig. 3). Thus the low nitrogen content in the water and the high one in the sediments indicate a high-rate accumulation of this element in the sediments of these five lakes.

In summer, the content of organic nitrogen in the sediments of the dimictic lakes ranged from 0.7 to 1.9% d. wt (Table II). The highest values were recorded at this time in four lakes with a high trophic state (Juno Południowe, Juno Północne, Sztumskie, Wobel), and in four lakes with a low trophic state (Sarż, Piłakno, Kuc, Probarskie; Fig. 3). By comparison with the spring period, the summer content of organic nitrogen in the sediments was primarily higher in lakes Juno Północne, Juno Południowe, Sztumskie and Wobel, and to a lesser extent - in lakes Małszewo, Rzeckie and Kierzlińskie (Fig. 3). In these lakes the summer content of organic nitrogen in the sediments is higher on an average by 27%, relative to its spring level.

In the remaining dimictic lakes the content of organic nitrogen in the sediments was lower in summer on an average by 18% of its spring level. As in spring, there was no clear summer tendency indicating an increase in the content of organic nitrogen in the sediments and total nitrogen in the water (Table II, Fig. 3).

The content of organic nitrogen in the bottom sediments of the polymictic lakes in spring and summer varied less than in the dimictic lakes, ranging from 1.0 to 2.1%, and from 0.9 to 2.1% d. wt (Table II). Except for Lake Będze, in which the content of organic nitrogen in the sediments was high in both spring and summer, differences among the polymictic lakes in respect of the content of organic nitrogen in the sediments in spring were small (Table II). They were clearly more marked in the summer period (Table II, Fig. 4). An increase in the content of nitrogen in the sediments was found in lakes Sasek Mały, Iławskie, Kołowin, Mój, Brajnickie, Sambród, Hartowiec, on an average by 18%. In the remaining lakes the content of organic nitrogen in the sediments was lower in summer on an average by 15%.

4. DISCUSSION

In the periods analysed the content of organic matter in the bottom sediments of dimictic lakes (except the sediments of Lake Gim where its concentration was high - over 70% d. wt), ranged from

9.5 to 49.4% d. wt. Higher levels were found in poorly mixed, static dimictic lakes with a low or with a high trophic state. In the polymictic lakes, the content of organic matter in sediments varied in the periods studied between 22.0 and 60.5% d. wt, its highest levels being found in lakes of a high trophic state. The differences in its content in the bottom sediments of the dimictic and polymictic lakes were thus considerable. They indicate a varying rate of organic matter accumulation in the sediments of the different lakes, and a varying degree of its mineralization.

The content of total phosphorus in the sediments varied over a wide range, 0.1-1.3% d. wt. The content of total phosphorus is lower in polymictic lakes than in dimictic lakes. The main component of total phosphorus in the bottom sediments of the lakes under study is organic phosphorus. It represents on an average about 56% of total phosphorus in dimictic lakes, and about 66% in polymictic lakes. The release of phosphorus from the sediments as a result of the mineralization of organic matter is much slower in dimictic than in polymictic lakes. This results from differences between these lake types in respect of water temperatures in summer (Z d a n o w s k i 1983).

In polymictic lakes, the important factors that accelerate the exchange of nutrients between the water and the bottom sediments are an intensive water mixing by the wind, lifting of lighter sediment fractions by the moving water, the release of gases and the stirring of sediments by the bottom fauna (H a m m 1971, K a j a k et al. 1975, K a j a k 1976, 1979, J a c o b s e n 1978).

In summer, in dimictic lakes with a low trophic state the predominating process was the release of the mineral fraction of phosphorus from the bottom sediments and water. With a higher level of total phosphorus in the sediments, on an average by 28%, the summer content of mineral phosphorus was lower, on an average by 37% than the spring content. In summer, changes in the level of mineral phosphorus in the sediments are concordant with the increasing concentration of total and phosphate phosphorus in the near-bottom water layer. The rate of accumulation of total and phosphate phosphorus near the bottom rises with the rising trophic state of lakes (Z d a n o w s k i 1983).

Among dimictic lakes there is a group with a large load of phosphorus (1.8-2.7 $g \cdot m^{-2} \cdot year^{-1}$; K a j a k and Z d a n o w s k i 1983): Juno Północne, Juno Południowe, Ełckie, Sztumskie and Wobel.

These are lakes of a high trophic state. In comparison with the spring, the summer level of total and organic phosphorus in the bottom sediments and near-bottom water layer of these lakes was higher, and so was, in some of them, the level of total phosphorus in the epilimnion.

In polymictic lakes, the direction of changes in the content of the various forms of phosphorus in the sediments differs from that observed in dimictic lakes. Though the content of organic phosphorus is higher than in dimictic lakes (on an average by 10%), it is primarily this fraction that accounts for the lower summer content of total phosphorus in the sediments, relative to the spring. In summer, the concentration of organic phosphorus in the bottom sediments of polymictic lakes is on the average lower by 23%, with only a slightly lower level of mineral phosphorus, by about 7%. At that time the content of total phosphorus in the water of polymictic lakes increases on an average by about 70%.

The above changes in the content of total and organic phosphorus in the sediments and in the water indicate a high rate of cycling of this element in polymictic lakes. In summer, under conditions of an intensive mixing, good oxygenation and a high pH in the near-bottom water layer the water in these lakes is intensively enriched with phosphorus. This process is intensified with rising water temperatures from spring to summer, and also with the rising trophic state of lakes (Z d a n o w s k i 1983).

The content of organic nitrogen in the bottom sediments of di- and polymictic lakes does not vary much from lake to lake within the two mictic types, or their trophic groups. No increase in the concentration of organic nitrogen in the sediments, associated with the rising trophic state, has been found for the lakes of both mictic types.

During the growing season, changes in the content of organic nitrogen in the sediments varied from lake to lake within the dimictic and polymictic types, and their trophic groups. In di- and polymictic lakes of a high trophic state a growth was observed of the summer content of organic nitrogen in the sediments and an accumulation of ammonia in the near-bottom waters. In dimictic lakes of a low trophic state, the summer level of organic nitrogen in the bottom sediments lowered on an average by 18%, relative to its spring level. These changes were accompanied by an increase in the content of ammonia near the bottom in summer (Z d a n o w s k i 1983). In polymictic lakes of a lower trophic state, the content of organic nitrogen in the sediments falls in summer on an average by 18%, relative to its spring level. This corresponds with the summer increase in the content of total nitrogen in the surface and near-bottom water layers, on an average by 12%, relative to the spring level (Z d a n o w s k i 1983). Changes in the content of organic nitrogen in the sediments and in the water indicate a summer enrichment of polymictic lakes with nitrogen.

ACKNOWLEDGMENTS: The author wishes to cordially thank A. Korycka, M. Sc., and Prof. Z. Kajak, Dr. Sc., for their penetrating and critical comments on the paper, and R. Wiśniewski, Dr. Sc., and K. Dusoge, Dr. Sc., for collecting bottom sediment samples from most of the lakes under study.

5. SUMMARY

The content was compared of organic matter, total, organic and mineral phosphorus, and of organic nitrogen in the bottom sediments of 37 lakes in north-eastern Poland (Table I). A description of the lakes can be found in the paper by K a j a k and Z d a n o w s k i (1983).

The studies were carried out during the spring circulation (April-May) and during the summer stagnation (August) in 1977 and 1978. Samples for analyses were taken from the 0-2 cm bottom-sediment layer in the deepest lakes zones. Changes in the content of phosphorus and nitrogen in the sediments were compared with changes in the level of phosphorus and nitrogen in the near-bottom water layer. The changes were assessed during the growing season over the trophic gradient (according to the summer content of total phosphorus in the epilimnion) separately for dimictic and polymictic lakes (Table II).

In dimictic lakes, the content of total phosphorus and total nitrogen in the near-bottom water layer increased in spring and summer together with the rising trophic state of the lakes (Table II). In bottom sediments the highest levels of total, organic and mineral phosphorus, of organic nitrogen and organic matter were found in lakes with the highest and those with the lowest trophic

state (Table II). In dimictic lakes characterized by a high trophic state (Czos, Ełckie, Juno Południowe, Juno Północne, Rzeckie, Sztumskie, Wobel) the summer content of total phosphorus in the sediments was higher than the spring content. In other dimictic lakes the content of total phosphorus in the sediments was lower in summer than in spring (Fig. 1). In summer, in most of the lakes a lowered level (by 7-77%, on an average by 37%) of the mineral fraction of total phosphorus is found relative to the spring, and a higher level of organic phosphorus (on an average by 28%, relative to the spring level) (Fig. 1).

The content of organic nitrogen in the sediments increases in summer in the following lakes: Juno Północne, Juno Południowe, Rzeckie, Wobel, Małszewo, Kierzlińskie and Sztumskie (on an average 27%, relative to the spring level). In other dimictic lakes the by content of organic nitrogen is lower in summer on an average by 18%, relative to the spring concentration (Fig. 3).

In polymictic lakes, in spring and summer the content of total phosphorus in the near-bottom water layer increased, and so did the content of organic matter and of total, organic and mineral phosphorus in the bottom sediments, with the rising trophic state (Table II).

The content of total and organic phosphorus in the sediments of most polymictic lakes decreases in the summer period, relative to the spring period on an average by 23 and 26%. The level of mineral phosphorus is lower in summer only by 7%. The above changes in the level of total and organic phosphorus in the sediments during the growing season lead to an intensive summer enrichment of water in polymictic lakes with phosphorus (Fig. 2).

The bottom sediments of polymictic lakes did not differ much in respect of the content of organic nitrogen in spring (Fig. 4). The content of organic nitrogen in the sediments of some lakes increased in summer on an average by 15%, relative to the spring level, whereas in the majority of lakes it decreased in the same period on an average by 15%, relative to the spring level (Fig. 4).

6. POLISH SUMMARY

Porównano zawartość materii organicznej, fosforu ogólnego, organicznego i mineralnego oraz azotu organicznego w osadach dennych, w 37 jeziorach położonych w północno-wschodniej Polsce (tab. I).

Charakterystykę jezior podano w pracy K a j a k a i Z d a n o w s k i e g o (1983).

Badania prowadzono w okresie wiosennej cyrkulacji (kwiecień-maj) i letniej stagnacji (sierpień) w 1977 i 1978 r. Analizowano 0-2 cm osady denne w najgłębszej strefie jeziora. Zmiany zawartości fosforu i azotu w osadach porównano ze zmianami stężeń fosforu i azotu w przydennej warstwie wody. Charakterystykę tych zmian w sezonie i w gradiencie trofii oceniono oddzielnie dla jezior dymiktycznych i polimiktycznych, wg letniej zawartości fosforu ogólnego w epilimnionie (tab. II).

W jeziorach dymiktycznych zawartość fosforu ogólnego i azotu ogólnego w przydennej warstwie wody wzrasta wiosną i latem wraz ze wzrostem trofii jezior (tab. II). W osadach dennych najwyższe stężenia fosforu ogólnego, organicznego i mineralnego, azotu organicznego i materii organicznej stwierdzono w jeziorach dymiktycznych o najwyższej i najniższej trofii (tab. II). Letnia zawartość fosforu ogólnego w osadach jest wyższa niż wiosną w jeziorach dymiktycznych charakteryzujących się wysoką trofią (Czos, Ełckie, Juno Południowe, Juno Północne, Rzeckie, Sztumskie, Wobel). W innych jeziorach dymiktycznych zawartość fosforu ogólnego w osadach jest niższa latem niż wiosną (rys. 1). W większości jezior stwierdza się latem obniżenie stężenia frakcji mineralnej fosforu ogólnego o 7-77% (przeciętnie o 37% jego wiosennego stężenia) oraz wzrost stężenia fosforu organicznego (przeciętnie o 28% wiosennego stężenia) (rys. 1).

Zawartość azotu organicznego w osadach wzrasta latem w jeziorach Juno Północne, Juno Południowe, Rzeckie, Wobel, Małszewo, Kierzlińskie i Sztumskie (przeciętnie o 27% jego wiosennego stężenia). W pozostałych jeziorach dymiktycznych zawartość azotu organicznego obniża się latem przeciętnie o 18% wiosennej koncentracji (rys. 3).

W jeziorach polimiktycznych stwierdzono wiosną i latem wzrost zawartości fosforu ogólnego w przydennej warstwie wody oraz wzrost stężeń materii organicznej, fosforu ogólnego, organicznego i mineralnego w osadach dennych wraz ze wzrostem trofii (tab. II).

Zawartość fosforu ogólnego i organicznego w osadach w większości jezior polimiktycznych, obniża się latem w stosunku do wiosny przeciętnie o 23 i 26%. Zawartość fosforu mineralnego jest niższa latem jedynie o 7%. Powyższe zmiany zawartości fosforu ogólnego i organicznego w osadach w sezonie prowadzą do silnego, letniego wzbogacenia jezior polimiktycznych w fosfor (rys. 2).

Wykazano słabe zróżnicowanie osadów dennych jezior polimiktycznych pod względem zawartości azotu organicznego w okresie wiosennym (rys. 4). Zawartość azotu organicznego wzrasta latem w osadach niektórych jezior, przeciętnie o 15% wiosennego stężenia, a w większości obniża się latem przeciętnie o 15% wiosennego stężenia (rys. 4).

7. REFERENCES

1. F e e E. J. 1979 - A relation between lake morphometry and primary productivity and its use in interpreting whole-lake eutrophication experiments - Limnol. Oceanogr. 24: 401-416.
2. G o l a c h o w s k a J. 1977 - Oznaczanie całkowitej zawartości fosforu mineralnego i organicznego w osadach dennych jezior [Determining total mineral and organic phosphorus content in bottom sediments of lakes] - Roczn. Nauk roln., Ser. H, 98: 39-49.
3. H a m m A. 1971 - Methodik der Untersuchung von Abwasser und Forfluter - Müncher Beitr. Abwass. Fisch. Flussbid. 19: 97-113.
4. H i l l b r i c h t - I l k o w s k a A., Z d a n o w s k i B. (in press) - The sensitivity of lakes to inorganic enrichment stress - some results from the experimentally induced eutrophication - Int. Rev. ges. Hydrobiol.
5. J a c o b s e n O. S. 1978 - A description model for phosphate sorption by lake sediments (In: Interactions between sediment and water, 6-th Nordic Symposium on Sediments, 9-12.03.1978, Hurdal, Norway) - Publication No. 304 from Freshwater Biological Laboratory, University of Copenhagen, 127-136.
6. K a j a k Z. 1976 - Sedymentacja a eutrofizacja wód [Sedimentation and eutrophication of waters] - Materiały Konferencji „Nawożenie a Eutrofizacja Wód", Zielona Góra, 141-162.
7. K a j a k Z. 1979 - Eutrofizacja jezior [Eutrophication of lakes] - Państwowe Wydawnictwo Naukowe, Warszawa, 233 pp.
8. K a j a k Z., K a c p r z a k K., P o l k o w s k i R. 1965 - Chwytacz rurowy do pobierania prób dna [Tubular bottom sampler] - Ekol. pol. B, 11: 159-165.
9. K a j a k Z., W i ś n i e w s k i R., R y b a k J. I. D u s o g e K. 1975 - Ecosystem of the Mikołajskie Lake. The fate of organic matter of the profundal zone - Pol. Arch. Hydrobiol. 22: 89-99.

10. K a j a k Z., Z d a n o w s k i B. 1983 - Ecological characteristics of lakes in nort-eastern Poland versus their trophic gradient. I. General characteristics of 42 lakes and their phosphorus load. Study objectives and scope - Ekol pol. 31:239-256.

11. K e m p A. L. W., M u d r e c h o v a A. 1972 - Distribution and forms of nitrogen in a lake Ontario sediment core - Limnol. Oceanogr. 17: 855-867.

12. P a t a l a s K. 1960 - Mieszanie wody jako czynnik określający intensywność krążenia materii w różnych morfologicznie jeziorach okolic Węgorzewa [Mixing of water as the factor defining intensity of food material circulation in morphologically different lakes of Węgorzewo district] - Roczn. Nauk roln., Ser. B, 77: 223-242.

13. S t a n g e n b e r g M. 1938 - Skład chemiczny osadów głębinowych jezior Suwalszczyzny [Die chemische Zusammensetzung der Tiefsedimente in den Seen des Suwałki Gebiets] - Rozpr. Sprawozd. Inst. Badaw. Lasów Państwowych, A-31: 1-44.

14. T r i f o n o v a N. A. 1974 - Soderžanie i vydelenie soedinenij azota donnymi otloženijami Rybinskogo Vodochranilišča - Trudy Akad. Nauk SSSR, Inst. Biol. Vnutr. Vod, 29: 68-89.

15. Z d a n o w s k i B. 1983 - Ecological characteristics of lakes in north-eastern Poland versus their trophic gradient. III. Chemistry of the water in 41 lakes - Ekol. pol. 31:287-308.