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Phytoplankton of Lake Żarnowiec against the background of changes in habitat conditions brought about by the action of the pumped-storage power station
1. Habitat conditions

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Abstract - Before the pumped-storage power station was put into commission, a regular cycle of changes in the physico-chemical parameters of the surface water was observed. The working of the power station eliminated of distinctly shortened the occurrence of situations typical of late autumn and summer. The dominating systems of parameters in the lake were characteristic of spring and early autumn.

Key words: lakes, pumped-storage power station, mixing of water, physico-chemical parameters.

1. Introduction

The usage of lakes as reservoirs in the process of energy production in pumped-storage, thermal, and nuclear power stations brings about the occurrence of environmental conditions which are untypical of naturally developed communities. As an effect of these changes there appear simultaneous and directional responses of individual phyto- and zoocenoses. Numerous works have been concerned with this problem. In Poland they dealt chiefly with the Konin lakes (Sosnowska 1974, 1988, Hillbricht-Ilkowska et al. 1976, Simm 1988, Zdanowski 1988). However, those studies did not take into consideration the period of natural functioning of lakes. When Lake Żarnowiec was included in the system of the pumped-storage power station as the lower reservoir, an investigation of the effects of intensified movement of water masses on the seasonal cycle of changes in the physico-chemical parameters of the water and on the phytoplankton became possible.

The aim of the present work was to determine changes in the physico-chemical parameters of the water in Lake Żarnowiec.

2. Study area

Lake Żarnowiec lies in the Gdańsk province at a distance of about 5 kilometres from the Baltic Sea, at the bottom of a uniformly wide and straight depression called the Żarnowiec Depression, of south-southeastly direction. Morphometric data concerning the lake are given in Table I.

Table I. Morpgometric charcters of Lake Żarnowiec. * – data supplied by the Inland Fisheries Institute; ** – according to Energoprojekt

Index	Conditions in the period	
	1956 - 1981*	1982 - 1987**
Average water level in the lake (m above sea level)	1.34	1.50
Area (ha)	1 431.6	1.413
Maximum depth (m)	19.4	19.6
Mean depth (m)	8.4	8.9
Relative depth $\frac{\text{Max. depth}}{\text{Area}}$	0.0051	—
Depth indicator $\frac{\text{Mean depth}}{\text{Max. depth}}$	0.4	—
Capacity (milion m^3)	120.84	120
Maximum lenght (m)	7 610	—
Maximum width (m)	2 600	—
Lenght of the shoreline (km)	18.7	—
Development of the shoreline	1.39	—

The catchment basin of the lake, with an area of 248.9 km^2, is composed of the river basin of the Rivers Piaśnica (87.5 km^2) and the Bychowska Struga (122.5 km^2) and of a direct one (38.9 km^2). In the years 1971-1975 the surface feeders, the Piaśnica and Bychowska Struga, brought in about 66 million m^3 of water annually (M i k u l s k i 1983). The single natural outflow, a sector of the Piaśnica, 5 km in length, discharged about 78 million m^3

water directly into the Baltic Sea. An underground outflow also had a large share in the water balance of the lake (M i k u l s k i 1983). According to this author, in the period 1961-1975 the water of the entire lake was exchanged on the average after a year and 5 month.

In the natural conditions the average annual level of the water surface was at a constant 1.28-1.34 m above sea level, average seasonal differences between maximum and minimum varying from 32-86 cm. The diel average variation of the water level was 1-2 cm, with a maximum of 5-7 cm (M a j e w s k i unpubl.).

In 1982 the pumped-storage power station which uses Lake Żarnowiec as its lower reservoir, was put into operation. An artificial upper reservoir with a total capacity of 15.9 million m^3 and the usable capacity of 13.6 million m^3 was located on the adjacent hills (about 100 m above sea level). The water flow in the channel connecting the lake with the power station can vary from 507-598 $m^3 s^{-1}$ in the period of water intake and about 700 $m^3 s^{-1}$ during its discharge. In the first year the power station operated only from 10th May to about 20th July. After a two-month break it started again after 10th September (M a j e w s k i unpubl.).

In 1982-1983 the running of the power station brought about a considerable increase - up to 37 cm on the average - in the diel variation in the water level. The amplitude of variation of the water surface was usually higher in winter, e.g., 47-48 cm in November and December 1982, and slightly lower in summer, e.g., 31 cm in May and 36 cm in August 1983 (K a z i m i e r s k i unpubl.). In 1984 the action of the power station was stabilized and the diel variation in the water level rose to 70-80 cm (K a z i m i e r s k i unpubl.). The annual cycle of changes of the amplitude did not change.

3. Material and methods

In the present work the results of physico-chemical investigations of the water from the years 1981-1983 were used. Some of these results were published by Z d a n o w s k i et al. (1986). They were supplemented by investigations carried out monthly from April to November 1984 at two stations. One was established in the middle of the lake at the place of maximum depth (16 m) and the other in the littoral at a finishing wharf at Nadole (a maximum of 1 m). Additional samples were taken in the middle of the lake in August 1985. The sampling and analyses were carried out similarly as in the work by Z d a n o w s k i et al. (1986).

For all samples 18 chemical parameters were characterized: oxygen consumption, pH, content of total nitrogen, total phosphorus, oxygen, silicon, and also calcium, magnesium potassium, sodium, ammonium, bicarbonate, carbonate, sulphate, chloride, nitrite, nitrate, and phosphate ions, and two physical ones: electrolytic conductivity and water temperature.

In elaborating the results the programs of hierarchic clustering HIERARG (G. Henrion et al. 1988), DIVA (R. Henrion et al. 1988), and principal components analysis (A. Henrion et al. 1987), written by the Chemistry Department of Humboldt University, Berlin, were used.

4. Results

The results of determinations concerning the chemical composition of 62 water samples taken both at the station in midlake and in the littoral were subjected to clustering analysis. Dendrograms were obtained by the agglomeration methods of hierarchic clustering: the division method according to the criterion of preserving the minimum variance in the formation of clusters, shown in fig. 1, the WARD method (fig. 2), and the method of averaged linkage (fig. 3).[1)]

All the dendrograms show a great similarity of the chemical composition of the water in the pelagial and the littoral. The first two-element clusters usually include water samples taken from the two stations on the same day. The number of samples which are exceptions to this rule, is different from each dendrogram. The smallest, concerning six pairs of results (from July and December 1981, July 1982, and August, October, and November 1983), were obtained in constructing a dendrogram using the divisive method (fig. 1).

[1)]The basic feature of hierarchic classifications is that the algorithm which ordinates an element into a cluster (class, group) never changes this ordination, i.e. no object changes from one class to another. The agglomeration (linkage) methods begin the classification process from the level of single objects. The most similar objects are gradually linked in larger and larger clusters up to the formation of one class covering all initial elements. The divisive methods carry out the classification process in a reverse direction; i.e., first of all objects are grouped in one class and in the first stop such a division of this class in two is sought which is most favourable as against the classification criterion. The way of functioning of algorithms shows that the divisive methods are in general more reliable than the agglomeration ones, in which the final result of classification may be distorted by possible erroneous decisions at low levels (Macnaughton-Smith et al. according to R. Henrion et al. 1988).

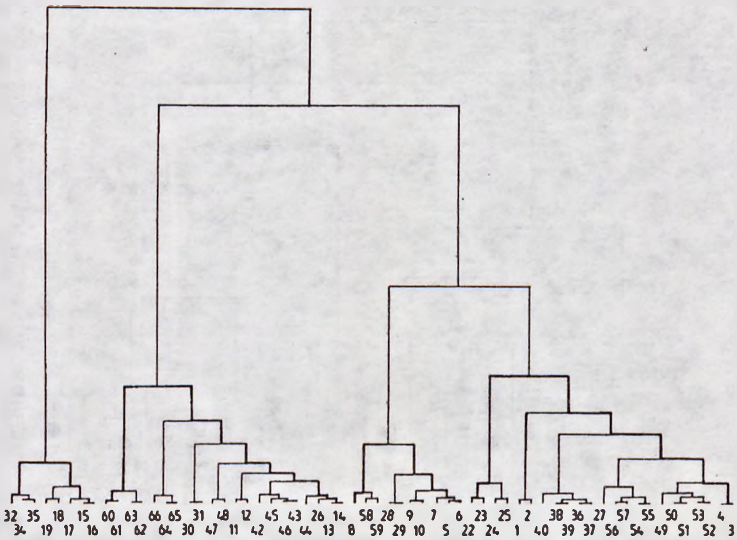

Fig. 1. Dendrogram obtained using the DIVA method of hierarchic clustering from the matrix of 20 physico-chemical parameters and 62 surface water samples taken at the pelagic (P) and littoral (L) stations in Lake Żarnowiec. Symbols:

1 – 6.04.1981 P,	2 – 7.04.1981 L,	3 – 4.05.1981 P,	4 – 5.05.1981 L,
5 – 2.06.1981 P,	6 – 2.06.1981 L,	7 – 8.07.1981 P,	8 – 8.07.1981 L,
9 – 5.08.1981 P,	10 – 5.08.1981 L,	11 – 8.09.1981 P,	12 – 7.09.1981 L,
13 – 7.10.1981 P,	14 – 7.10.1981 L,	15 – 3.11.1981 P,	16 – 3.11.1981 L,
17 – 10.12.1981 P,	18 – 10.12.1981 L,	19 – 8.02.1982 P,	22 – 4.05.1982 P,
23 – 4.05.1982 L,	24 – 7.06.1982 P,	25 – 7.06.1982 L,	26 – 5.07.1982 P,
27 – 5.07.1982 L,	28 – 3.08.1982 P,	29 – 3.08.1982 L,	30 – 7.09.1982 P,
31 – 7.09.1982 L,	32 – 12.10.1982 P,	34 – 9.11.1982 P,	35 – 3.11.1982 L,
36 – 11.04.1983 P,	37 – 11.04.1983 L,	38 – 3.05.1983 P,	39 – 3.05.1983 L,
40 – 6.06.1983 P,	42 – 4.07.1983 P,	43 – 1.08.1983 P,	44 – 1.08.1983 L,
45 – 6.09.1983 P,	46 – 11.10.1983 P,	47 – 11.10.1983 L,	48 – 3.11.1983 P,
49 – 3.11.1983 L,	50 – 13.04.1984 P,	51 – 13.04.1984 L,	52 – 8.05.1984 P,
53 – 8.05.1984 L,	54 – 7.06.1984 P,	55 – 7.06.1984 L,	56 – 4.07.1984 P,
57 – 4.07.1984 L,	58 – 8.08.1984 P,	59 – 7.08.1984 L,	60 – 5.09.1984 P,
61 – 5.09.1984 L,	62 – 10.10.1984 P,	63 – 11.10.1984 L,	64 – 6.11.1984 P,
65 – 6.11.1984 L,	66 – 30.08.1985 P,		

Dendrograms obtained by the linkage method (and thus, more precisely reflecting the similarity relations between the elements which form small clusters - the lower part of the dendrogram) show a slightly greater differentiation between the two stations. In the dendrogram obtained by the WARD method already 10 such pairs of data appear (fig. 2). To the ones previously shown two were added

Fig. 2. Dendrogram obtained using the WARD method of hierarchic clustering from the matrix of 20 physico-chemical parameters and 62 surface water samples taken at the pelagic (P) and littoral (L) stations in Lake Żarnowiec. Symbols as in fig. 1

in 1981 (June and August) and two in 1982 (May and June). In the construction of a dendrogram using the method of averaged linkages one more pair from September 1981 is added (fig. 3).

The greatest differentiation in the chemical composition of the water from the two stations appears in the summer

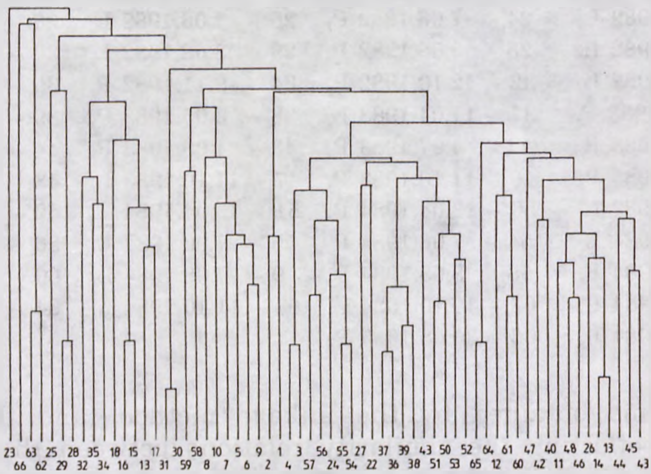

Fig. 3. Dendrogram obtained using the method of hierarchic clustering of averaged linkages from the matrix of 20 physico-chemical parameters and 62 surface water samples taken at the pelagic (P) and littoral (L) stations in Lake Żarnowiec. Symbols as in fig. 1

(June-September) 1981 (five pairs of samples). The remaining six cases were found in the two successive year 1982 and 1983. In 1984 no such differences were noted. On the other hand, the differences in the chemical composition of the water at the two stations were slight, since in no dendrogram was there ever formed a group of a few, let alone of several elements, clustering samples from one station.

Two dendrograms obtained by methods in which the maintenance of a minimum variance within all clusters is used as the criterion of division or linkage, show the existence of four clusters differentiated to a fairly distinct degree. In these dendrograms the ordination of individual water samples is not identical. Twelve samples were differently classified.

The dendrogram obtained using the method of averaged linkage distinctly shows that in general the range of variation of the analysed parameters is fairly narrow and at the same time not discrete.

All the discussed samples of water, described by the same 20 parameters, were also subjected to principal component analysis (PCA).[2)] The obtained ordination is shown in fig. 4. The first axis explains 19.9%, the second 13.6%, and the third not much less, i.e. 12.2% of the total variance. Therefore, the ordination in relation to the first and second axis elucidates 33.6% of the total variance.

The comparison of results obtained by PCA analysis and cluster analysis permits the statement that the classification made on the basis of the divisive method is most suitable for ordination against the first two main components (the dendrogram in fig. 1). Therefore, and also because of the fact that the divisive methods usually more correctly arrange elements in the clusters of a higher order, the classification obtained by the divisive method according to the criterion of the minimum variance was accepted in further discussion. Table II contains averages and confidence intervals for averages of the analysed parameters in four differentiated clusters; fig. 5 presents the distribution of elements of these clusters in time.

[2)]The ordination (arrangement) methods are used with the aim of presenting the gradient structure of the analysed sample. The obtained result is such an ordination of objects, in two-dimensional or at the most three-dimensional space, that from the distances between the objects the connections of similarity between them may be read to the most exact possible degree (W i l d i 1986). The algorithm searches for new non-correlated axes, i.e. perpendicular to each other, called the main components, from which the variance of projections of points from n-dimensional (in this case n=20) space is maximal (A. H e n r i o n et al. 1987), this meaning that at the successive steps the algorithm seeks such straight lines as penetrate the cloud of objects in the direction in which this cloud is most elongated.

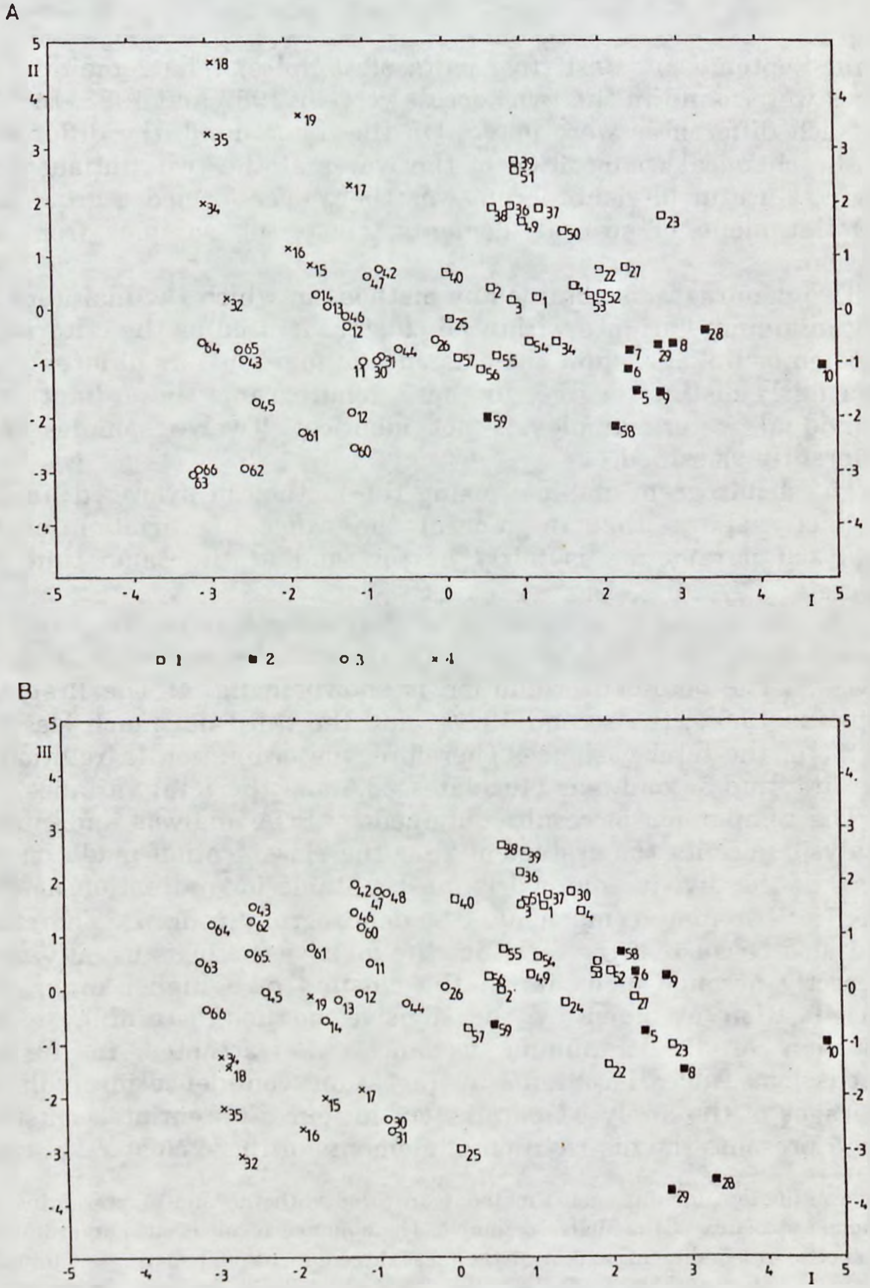

Fig. 4. Diagram of ordination against axes I and II (A) and I and III (B) of 62 surface water samples taken at the pelagic and littoral stations in Lake Żarnowiec, obtained using the method of principle component analysis (PCA) from 20 physico-chemical parameters of the water. Numbers beside the points refer to water samples and agree with fig. 1

Table II. Averages and confidence intervals of temperature (°C) and of basic components of water chemical composition (mg dm^{-3}) of the distinguished groups of physico-chemical parameters of the Lake Żarnowiec habitat in the period 1981-1984. Number of elements given in brackets

Parameter	Group			
	I (23)	II (10)	III (21)	IV (8)
Temperature	11.0 8.7-13.3	20.3 18.7-22.0	15.5 14.0-17.1	6.3 3.0-9.7
O_2	12.5 11.6-13.4	11.3 10.1-12.5	9.7 8.9-10.6	11.2 10.1-12.3
Ca	55.4 54.1-56.8	50.1 47.5-52.7	54.8 53.4-56.3	52.8 50.0-55.5
Mg	7.6 7.0-8.2	10.3 8.7-11.8	7.6 7.2-8.0	6.9 5.5-8.3
K	2.8 2.3-3.2	2.5 2.1-3.0	2.8 2.5-3.0	2.7 2.3-3.1
Na	10.9 10.4-11.4	10.7 9.8-11.6	11.1 10.8-11.5	9.6 9.3-10.0
HCO_3^-	143 139-147	136 124-147	148 144-153	145 142-148
CO_3^{-2}	2.9 2.0-3.9	4.3 2.9-5.6	0.6 0.2-1.0	0.0 —
SO_4^{-2}	31.8 29.9-33.6	26.3 23.5-29.1	32.8 30.8-34.8	29.1 27.7-30.4
Cl^-	20.5 20.2-20.8	21.3 20.7-22.0	20.5 20.2-20.9	19.7 19.1-20.3
SiO_2	3.4 2.6-4.1	3.0 1.5-4.6	5.3 4.2-6.4	10.4 8.8-12.0
NH_4-N	0.07 0.05-0.08	0.07 0.03-0.12	0.11 0.06-0.16	0.09 0.04-0.14
NO_2-N	0.008 0.006-0.011	0.004 0.001-0.007	0.013 0.009-0.017	0.009 0.006-0.011
NO_3-N	0.22 0.19-0.25	0.18 0.13-0.26	0.22 0.19-0.26	0.49 0.34-0.64
Tot-N	0.92 0.67-1.12	0.76 0.62-0.91	0.81 0.68-0.95	1.76 0.57-2.94
PO_4 - P	0.015 0.006-0.024	0.015 0.001-0.028	0.072 0.054-0.089	0.056 0.036-0.076
Tot -P	0.062 0.046-0.078	0.069 0.052-0.086	0.118 0.101-0.135	0.085 0.070-0.100
Oxygen consumption (mg O_2 dm^{-3})	7.9 7.4-8.5	8.9 8.3-9.6	6.4 5.9-7.0	8.2 7.0-9.4
pH	8.4 8.3-8.4	8.3 8.1-8.4	8.0 7.9-8.1	7.8 7.7-7.9
Specific electrolytic conductivity (μs cm^{-1})	346 341-352	339 321-355	341 336-347	343 330-356

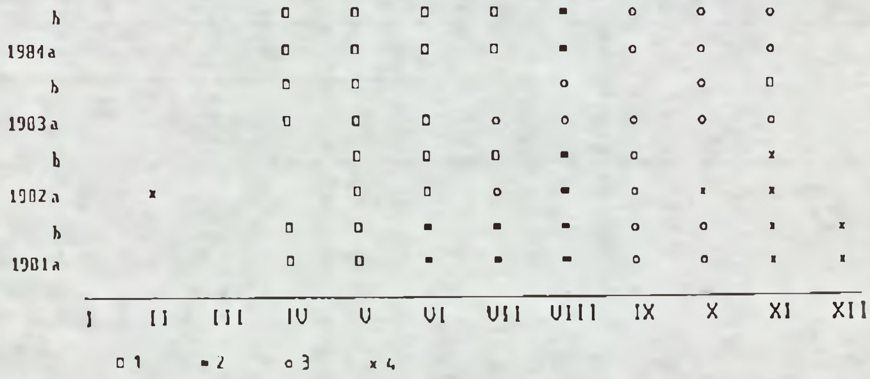

Fig. 5. The occurrence of distinguished groups of physico-chemical parameters of surface water from pelagic and littoral stations in Lake Żarnowiec in the period 1981-1984. 1 - group I; 2 - group II; 3 - group III; 4 - group IV; a - pelagic station, b - littoral station

Cluster I (23 elements, mostly occurring in the period April-June) is characterized by a mean temperature of 11°C, the highest oxygen concentrations of all analysed samples, increased pH of the water and calcium ion concentrations, and low concentrations of phosphate ions and total phosphorus. Cluster III (21 elements, mainly occurring in September and October) is the most similar to the above, differing in higher water temperatures, a lower content of oxygen and carbonate ions, lower pH of the water, and above all in very high concentrations of phosphate ions and total phosphorus. Cluster II (10 elements occurring only in summer, June-August) is characterized by the highest temperatures, low concentrations of phosphate and total phosphorus, and higher concentrations of carbonate and magnesium ions. Cluster IV includes 8 elements occurring in the months of October, December, and February. They show the lowest temperatures and pH, and above all a much higher concentration of total and nitric nitrogen but with average values of phosphates and total phosphorus than the other samples. This cluster was distinguished by all the algorithms of hierarchic clustering used.

5. Discussion

As compared with other freshwater reservoirs in Poland Lake Żarnowiec did not significantly differ in the ionic composition of the water. On account of the mean concentrations and high share of carbonate and calcium ions, Z d a n o w s k i et al. (1986) classified it as belonging to the calcium hydrocarbonate type. S z a r e j k o (1983) and Z d a n o w s k i et al. (1986) demonstrated that the lake always showed a small seasonal variation in its chemical composition and small differences in the concentration of individual components between the water layers and the sampling stations.

After the pumping-storage power station was put into operation a slight increase in the average concentration of calcium and carbonate ions, in electrolytic conductivity, and in the content of total nitrogen was observed (Z d a n o w s k i et al. 1986). However, only the analysis carried out in the course of the present study permitted the statement that at the two stations in the system April-May, June-August, September-October, and November-December all four of the distinguished clusters occurred, forming a regular picture of the cycle of changes in the physico-chemical traits of the habitat throughout the year (fig. 5). In 1982 certain disturbances appeared in this system. The discussed groups were also found at that time, but the situation typical of summer was distinctly reduced, the prolonged occurrence of traits of the habitat typical of early spring being at the same time noted. In July 1982 at the pelagic station the physico-chemical traits of the water approximated to the system characteristic for early autumn. The unquestionable reason for the prolongation was the starting up and fairly regular running (though not yet at full power) of the pumped-storage power station.

In 1983 there appeared a different type of changes in the physico-chemical properties of the lake water. Situations characteristic for summer and late autumn completely disappeared. In July there came a transition from the conditions typical of spring months to those of early autumn. A similar situation also appeared in 1984, with the reservation that the two periods i.e. spring (prolonged to July) and autumn, were divided by the system of parameters characteristic for summer.

In the aspect of the degree of eutrophication of the lake, a distinct earlier increase in the concentration of phosphorus in the pelagial, observed in 1983, was important, indicating an intensive process of internal enrichment of the lake with this element. It resulted from the occurrence of oxygenic-thermal stratification in a period shortened to only 2-4 weeks, as observed by Kazimierski (unpubl.) and Zdanowski et al. (1986), and hence of the intensification of phosphorus exchange between the water and bottom sediments.

6. Polish summary

Fitoplankton Jeziora Żarnowieckiego na tle zmian warunków siedliska wywołanych pracą elektrowni szczytowo-pompowej 1. Warunki siedliska

Na podstawie badań przeprowadzonych w latach 1981-1984, w oparciu o 18 parametrów chemicznych: utlenialności, odczynu, zawartości azotu ogólnego, fosforu ogólnego, tlenu, krzemu oraz jonów wapnia, magnezu, potasu, sodu, amonowych, wodorowęglanowych, węglanowych, siarczanowych, chlorkowych, azotynowych, azotanowych i fosforanowych oraz 2 fizycznych: przewodnictwa elektrolitycznego i temperatury, scharakteryzowano zmiany warunków fizyczno-chemicznych wody powierzchniowej Jeziora Żarnowieckiego, wywołane włączeniem tego zbiornika w 1982 roku w system elektrowni szczytowo-pompowej. Dane morfometryczne jeziora przedstawia tabela I.

Dendrogramy, uzyskane aglomeracyjną i podziałową metodą grupowania hierarchicznego (ryc. 1-3), wskazywały na bardzo duże podobieństwo cech fizyczno-chemicznych wody w pelagialu i litoralu. Największe zróżnicowanie wody obu stanowisk stwierdzono od czerwca do września 1981 roku. W kolejnych dwu latach było ono mniejsze. W 1984 roku nie stwierdzono go w ogóle. Zakres zmienności analizowanych parametrów był niewielki.

Porównanie wyników analizy głównych składowych (ryc. 4) i analizy skupień pozwoliło wyróżnić cztery grupy parametrów fizyczno-chemicznych wody. Tabela II przedstawia średnie i przedziały ufności średniej analizowanych parametrów w poszczególnych grupach. W 1981 roku obserwowano występowanie wszystkich wyróżnionych grup na obu stanowiskach (ryc. 5): od kwietnia do maja - grupa I, od czerwca do sierpnia - II, we wrześniu i październiku - III oraz w listopadzie i grudniu - IV. W 1982 wyraźnie ograniczona została sytuacja charakterystyczna dla lata, a jednocześnie wydłużone zostało występowanie cech siedliska typowych dla wczesnej wiosny. W 1983 obserwowano występowanie tylko dwu grup. Zaniknęły sytuacje charakterystyczne dla miesięcy letnich i późnojesiennych. W 1984 okres wiosenny i jesienny oddzielał jednak układ parametrów typowych dla lata (rys. 5).

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