ACTA HYDROBIOL.	34	4	389—400	KRAKÓW 1992

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

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Manuscript submitted August 3, 1992, accepted December 12, 1992

Abstract - The investigation of phytoplankton in Lake Żarnowiec was carried out prior to, in the course of construction, and after starting operation of the pumped-storage power station. On the basis of analysis of the developmental dynamics and dominance structure of species, the range and degree of derangement in the functioning mechanism of this community were demonstrated.

Key words: lakes, phytoplankton, pumped-storage power station, dynamics of development, dominance of species.

1. Introduction

The transformation of a phytoplankton community affected by changes in the intensity of water movement has been investigated by numerous workers. Their investigations chiefly concerned dam reservoirs (Pająk, Kiss 1990) or lakes which were included in the cycle of thermal power stations (Simm 1988, Sosnowska 1988). No works concerning changes in the structure and developmental dynamics of the phytoplankton in lakes included in the cycling of pumped-storage power stations are known to the author. Therefore, this problem became the subject of the present work.

The aim of this study was to determine the character and trend of changes in the phytoplankton community of Lake Żarnowiec, caused by inclusion of the lake in the cycle of a pumped-storage power station.

2. Study area

General information concerning the position of Lake Żarnowiec and its inclusion in the cycle of the pumped-storage power station can be found in Hutorowicz (1993).

In its natural state the content of phosphorus (average 0.090 mg dm^{-3}) was typical for eutrophic lakes (Zdanowski et al. 1986). However, the trophic condition of the lake may be determined as moderately eutrophicated. This was shown by the average visibility of a Secchi disc exceeding 3 m and in general low concentrations of chlorophyll, which sporadically exceeded 10 μg dm^{-3} (Hutorowicz, Zdanowski 1986). A weak oxygenic-thermal stratification usually formed at the turn of May. Depending on the direction and strength of the wind this was maintained during 1-3 months. The maximum temperature differences between the surface and bottom layers amounted to 12°C. Short-term oxygen deficiency of the order of 1 mg dm^{-3} chiefly appeared at the bottom in August (Hutorowicz 1991).

The physico-chemical traits of the water changed regularly during the vegetation season. Four groups of its physico-chemical parameters were differentiated. They determined the traits of the water in spring (April and May), summer (June-August), early autumn (September and October), and late autumn (November and December). The most significantly differentiating parameters were the concentrations of orthophosphate, nitrate, and carbonate ions, and also pH and temperature (Hutorowicz 1993).

The forced mixing of the water in the lake by the operation of the pumped-storage power station brought about significant changes in the vertical stratification. The period of occurrence of the oxygenic-thermal stratification was distinctly shortened to only 2-4 weeks. The greatest differences of temperature between the surface and near the bottom layer slightly exceeded at the outmost 7°C. They occurred at the turn of May at the time when the vertical stratification was being formed (Hutorowicz 1991). The cycle of changes in the physico-chemical parameters of the lake waters was also different. The traits characteristic for the spring were maintained up to June or even July. Then they were transformed, reaching values typical for early autumn. This system of parameters was preserved until November. Sometimes the two periods were divided by a short-term system of traits characteristic for summer (Hutorowicz 1993).

3. Material and methods

The study of phytoplankton was carried out in the period 1981-1984 and in 1988. Samples were taken monthly from April to November (in 1981 to December). Two stations were selected (Hutorowicz 1993).

Quantitative analysis of pelagic phytoplankton was carried out on the basis of three integrated samples taken from three water layers: from 0-5 m, 6-10 m, and 11 m above the lake bottom. The samples were taken with a Ruttner's dredge at 1 m intervals and then mixed in equal volume. From such a preparation about 150 cm^3 of water was drawn as a quantitative sample of the pelagic plankton of the given layer. Analogical sampling was conducted in the littoral from the surface to the bottom, i.e. 0-1 m. For the qualitative analysis of phytoplankton at least 25 dm^3 of water from each layer was filtered through a N° 25 plankton net. For quantitative determinations the samples were immediately fixed with a Lugol solution with sodium acetate.

The counting of organisms was carried out in an inverted microscope. Depending on the concentration, plankton were condensed directly in 5-20 cm^3 microscope chambers. The whole chamber was surveyed at low magnification (magnification x 5 of the objective) in order to count large species. The counting of individuals or the prevailing small species was carried out at an objective x 10 magnification, surveying two diameters of two chambers each. In determining the numbers of nanoplankton forms in each chamber the survey was made at an objective x 40 magnification in four strips of 27 fields of vision each.

The volume of phytoplankton calculated from their numbers and individual volume was used as the biomass index. For dominants the volume of individuals was calculated on the basis of dimensions obtained from measurements of 10-30 specimens from each sample. The volume of the remaining taxa was calculated according to the possibility of finding their representatives, the average values from a few months also being used. The total volume of many species was evaluated on the basis of the volume obtained for a genus and the percentage share of representatives of a given species among the representatives of the given genus. The volume of phytoplankton was calculated using the author's own "Biofit" program.

Identification of diatoms was carried out using the Krammer and Lange-Bertalot keys (1986, 1991). The nomenclature proposed by these authors was accepted.

4. Results

4.1. Phytoplankton biomass

In the years 1981 and 1982 the community of pelagic phytoplankton was characterized by rather small magnitudes of biomass. In the 0-5 m layer the annual mean biomass slightly exceeded 2 mg dm^{-3}. Two peaks of development occurred in the vegetation season. The spring peak was formed by diatoms, while the summer peak of biomass was brought about by diatoms and blue-green algae, and in 1981 and 1982 by blue-green algae only (fig. 1).

Subsequent years were characterized by different dynamics of development of the pelagic plankton community, undoubtedly caused by the movement of lake waters, which was more intensive than in natural conditions. In 1983 there were two peaks of plankton development - in spring and in late autumn - both having been brought about by diatoms (fig. 1). The autumn peak attained a value sporadically found in this lake, i.e. 7.9 mm^3 dm^{-3}. In 1984 diatoms were the only group with a larger biomass. Three peaks of development were observed - in spring, early summer, and September (fig. 1). In spring 1988 there appeared one distinct peak caused by diatoms (10 mm^3 dm^{-3}); its consequence was a fairly large biomass of plankton until towards the end of May. It was formed by green algae and diatoms (fig. 1).

In 1981 the littoral phytoplankton in general differed from the pelagic in having a markedly greater abundance (particularly in April and August). Because of the very large biomass of green (filamentous) algae, the summer peak occurred a month earlier then in pelagic phytoplankton (fig. 2). Similarly, in 1982 considerable differences were found between the two communities, both with regard to the intensity of development and to the main dominants. In August and October the green algae were also the group with a markedly greater abundance than the pelagic plankton (fig. 2).

In 1983 and 1988 the dynamism of development of the littoral plankton approximated to that observed in the pelagial.

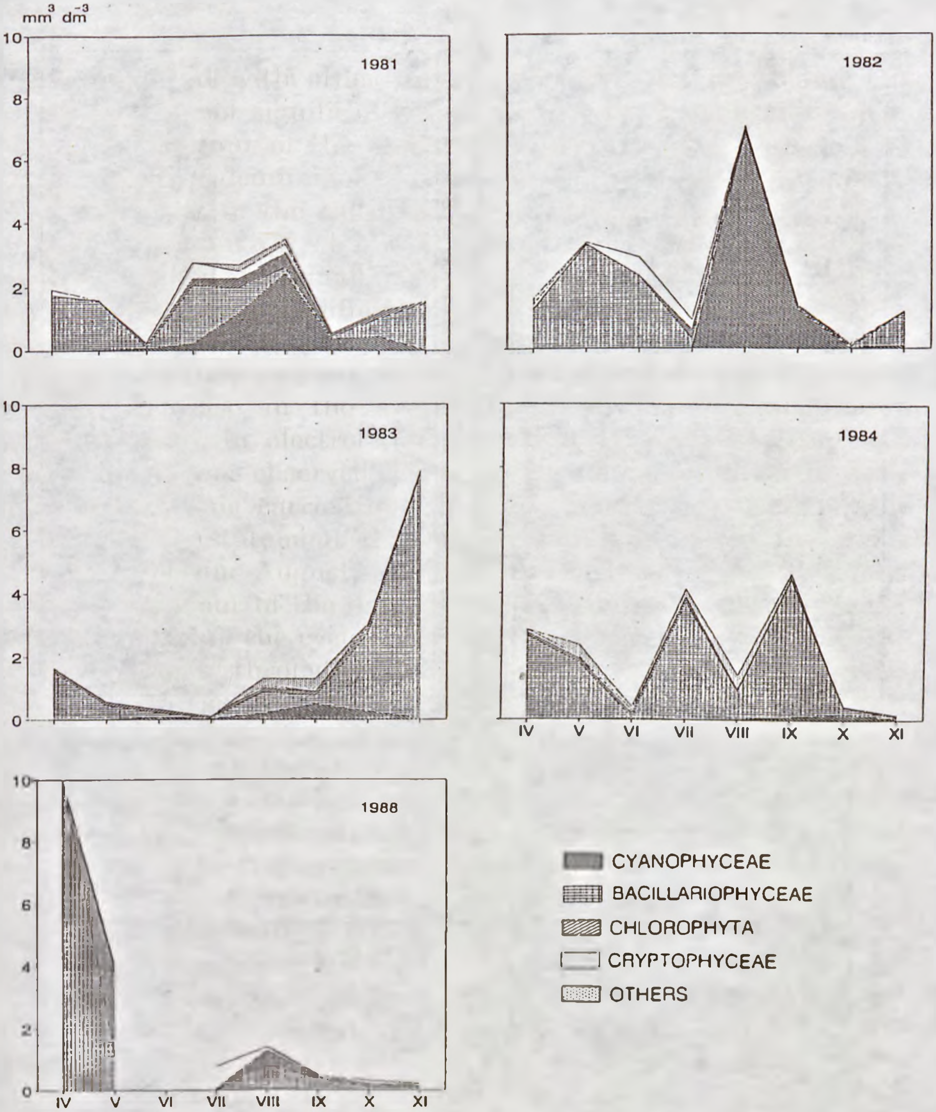

Fig. 1. Seasonal changes in the biomass (mm^3 dm^{-3}) of pelagic phytoplankton and the dominance of different taxonomic groups in Lake Żarnowiec in the period 1981-1984 and in 1988

The respective values of biomass magnitude were distinctly equated. The exceptionally different abundance of the littoral plankton in November 1988 was brought about by the disturbance of the littoral bottom by heavy equipment which was used in the construction of embankments along the lake shoreline. In 1984 the

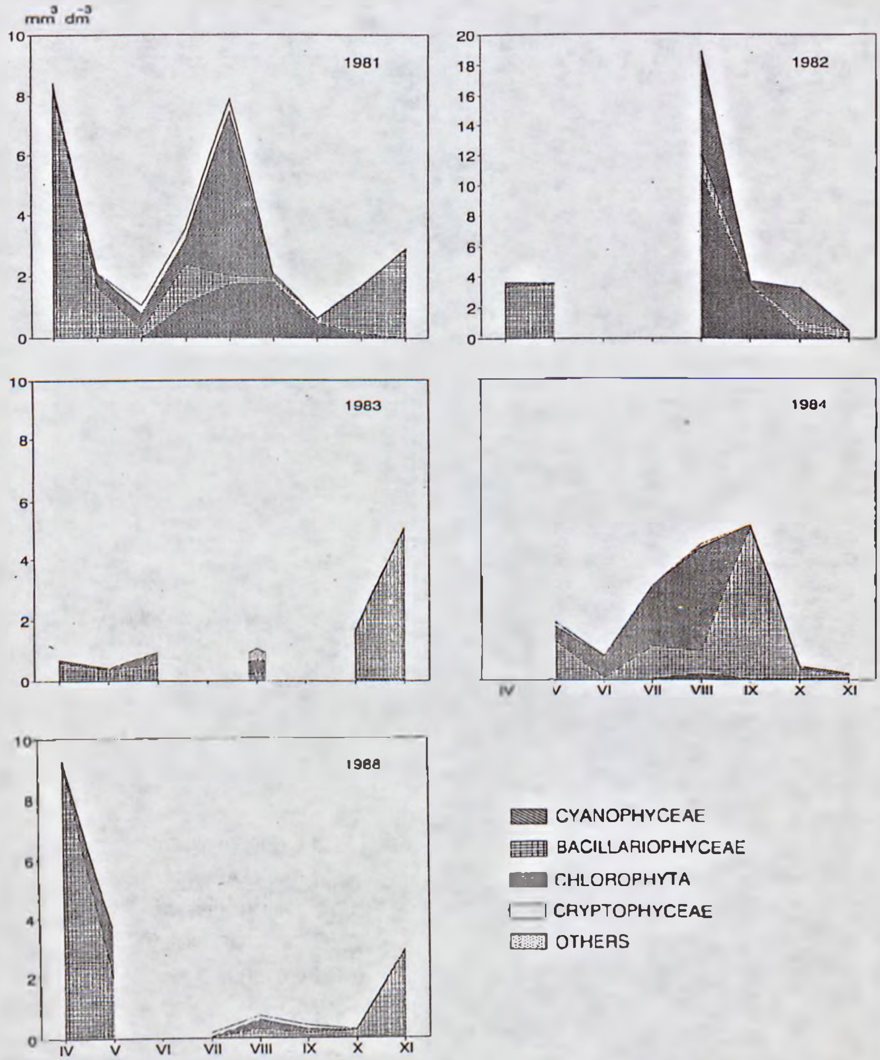

Fig. 2. Seasonal changes in the biomass (mm^3 dm^{-3}) of littoral phytoplankton and the dominance of different taxonomic groups in Lake Żarnowiec in the period 1981-1984 and in 1988

development of the littoral plankton varied decidedly from that in the pelagial of the lake. The type of the two peaks (the green alga-diatom spring peak and the diatom-green alga summer peak with a gradual transformation of dominance into that of diatoms, figs 1 and 2) occurred.

4.2. Species dominance

In the years 1981-1982 a similar type of seasonal dynamics of the pelagic phytoplankton community was not reflected in the developmental cycle of those species, which played a significant role with regard to biomass. In 1981 the April spring peak brought about in common by *Aulacoseira islandica* (O. Müller) Simonsen (48% of biomass), *Stephanodiscus* sp. (24%), *S. neoastraea* Hakansson et Hickel (11%), and *Cryptomonas* sp. (9%). In May the significant components of biomass were already *Cyclostephanos dubius* (Fricke) Round (25%), *Fragilaria ulna* (Nitzsch) Lange-Bertalot (20%), *Diatoma tenuis* Agardh (17%), and *Aulacoseira islandica* (13%). In July the dominance of *Fragilaria crotonensis* Kitton (42%), with *Asterionella formosa* Hassall (18%) and *Cryptomonas* sp. (19%) as co-dominants, was still observed. In August the blue-green algae *Microcystis aeruginosa* Kützing (19% and *Anabaena flos-aquae* Brébisson (14%) already played a significant role, though the large share of *Fragilaria crotonensis* (19%) was maintained. In September the genus *Microcystis* (62%) distinctly dominated with the monad forms *Chlamydomonas* sp. (11%) and *Cryptomonas* sp. (7%) as co-dominants. The dominance of *Microcystis* was maintained until October, gradually passing into the dominance of *Aulacoseira islandica* (84% in December). In contrast to 1981, in 1982 the decided dominant of April and May was *Asterionella formosa* (55 and 92% respectively). In June *Diatoma tenuis* (50%), *Asterionella formosa* (27%), and *Cryptomonas* sp. (20%) already constituted the biomass. *Anabaena flos-aquae* (92%) was the only dominant in August, in September the genus *Microcystis* (43%), and in November *Aulacoseira islandica* (85%).

In 1983 *Aulacoseira* was almost the only significant constituent of the phytoplankton with regard to abundance. In spring *Aulacoseira islandica* (76% in April and 44% in May), in October *A. granulata* (Ehrenberg) Simonsen (58%) and *A. islandica* (18%) dominated; in November *A. islandica* again appeared as the most significant constituent of the phytoplankton (77%). The share of *A. granulata* was 19% of the total biomass. Undoubtedly, in summer the very poor development of blue-green algae was caused by the water movement. In August *Fragilaria crotonensis* (32%) and *Ceratium hirundinella* (O.F. Müll.) Bergh (18%), and in September *C. hirundinella* (31%) and *Microcystis grevillei* (24%) prevailed. However, the absolute value of biomass of this blue-green alga was much lower than that in the previous year.

In 1984 the significant feature of the dominance structure (different from that of the natural state) was again the almost total elimination of blue-green algae and the shifting of *Aulacoseira* dominance to the summer peak. A much larger biomass of this genus was already noted in July and was constituted by *A. granulata* (12%) and *A. islandica* (13%). In August and September *A. granulata* distinctly dominated in the plankton (58% and 91%, respectively). A similar but much weaker tendency was also observed in 1988. Additionally, it was distinguished by a strong bloom of *Stephanodiscus hantzschii* (98%) and in May by the intense development of *Chlamydomonas* (66%).

In the littoral plankton the structure of dominance was in general similar to that in the pelagic, the filaments of green algae *Spirogyra* and *Mougeotia* not being taken into consideration. The most significant differences were found in 1981, when in April, apart from *Aulacoseira islandica* (29%), *Diatoma vulgaris* Bory (14%), *Fragilaria* sp. div. (30%), and *Navicula* sp. div. (12%) appeared as co-dominants. Also the pattern of development of the genus *Microcystis* was different: it co-dominanted already in July (17%) and decidedly prevailed in August (51%) and September (69%). In 1982, 1983, and 1984 the pattern of dominance was also similar to that in the pelagial, the only significant difference being found in the littoral in August 1982. *Anabaena flos-aquae* blooms (72%), analogical to those in the pelagial, were accompanied by a slightly greater abundance of the genus *Fragilaria* (9%). In 1984, apart from September when, as in the pelagial, *Aulacoseira granulata* (95%) dominated, from May to August the significant constituents of the littoral plankton were *Stephanodiscus* sp. (20%), *Fragilaria ulna* (17%), *F. crotonensis* (14%), and *Diatoma tenuis* (14%, with their total abundance under 2 mm^3 dm^{-3}) in May and in July *Asterionella formosa* (57%/22%) and *Aulacoseira granulata* (11%/5%). In May 1988 the *Fragilaria* genus (50%) dominated while the almost 5 times smaller biomass of *Chlamydomonas*, which dominated in mid-lake, constituted 23% of the total biomass (the biomass of *Ulothrix* of about 1 mm^3 dm^{-3} was not taken into consideration). The littoral station differed from the pelagic in the very abundant occurrence of filamentous green algae of the genera *Mougeotia* and *Spirogyra* in August 1981, in August and October 1982, and July and August 1984.

4.3. Vertical stratification

The vertical differentiation of the plankton biomass in the lake was chiefly observed in the period 1981-1982. In July 1981 in the

6-16 m layer the biomass of *Fragilaria crotonensis* was twice that at the surface. In April 1982 a reverse stratification of *Asterionella formosa* (0.9 mm^3 dm^{-3} in the 0-5 m layer, 1.2 in the 6-10 m layer, and 1.5 in the 11-16 m layer) was found. The sharpest vertical stratification occurred on August 5, 1982. It was brought about the concentration of *Anabaena flos-aquae* near the surface (in the distinguished strata 6.5, 1.6, and 0.4 mm^3 dm^{-3} were found). An analogical though much poorer stratification was observed in September 1982 (*Microcystis* ssp.), August (*Anabaena flos-aquae* and *Microcystis aeruginosa*), and September 1981 (*Microcystis* sp.).

In the period 1983-1984 and 1988 a much stronger mixing of the lake water was observed. The only significant vertical stratification was found in May 1988 owing to the concentration of the flagellate *Chlamydomonas* near the surface (2.8, 0.4, and 0.1 mm^3 dm^{-3} were found in the distinguished strata).

5. Discussion

Lake Żarnowiec may still be described as moderately eutrophicated owing to the slight load of phosphorus from its comparatively small immediate catchment area (Zdanowski et al. 1986), a considerable accumulation of phosphorus in the bottom sediments (Kajak et al. 1983), and the very abundant productivity of the littoral zone (filamentous algae loosely connected with the substratum, and aquatic plants). The accumulation of phosphorus and nitrogen loads, brought in by surface feeders of the lake, the Struga Bychowska and Piaśnica streams, is limited by the intensive water exchange in the reservoir (Zdanowski et al. 1986).

The first two years of the investigation in practice cover observations of the community in a natural state. Although in 1982 one block of the pumped-storage power station was already in operation in spring and autumn, the summer development of the phytoplankton was still determined only by natural conditions. With fairly great differences in the successive seasons, the plankton community developed according to the general scheme, i.e. the two biomass peaks. The spring peak was formed by diatoms of the genera *Fragilaria*, *Stephanodiscus*, and *Asterionella formosa*, and the summer peak by the blue-green algae *Anabaena flos-aquae* and *Microcystis* ssp. The peak of *Aulacoseira* development was reached in autumn. This type of dynamism of the pelagic plankton community did not happen by chance. It confirmed the results of studies on phytoplankton communities in the northern and southern parts of the pelagial, carried out by Sosnowska (1977) in 1974. Also as that time two peaks of development were observed, in spring and summer, though their intensity was much greater than in 1981-1984 and in 1988. As in 1981, blue-green algae of the genus *Microcystis* dominated then in the summer peak. In contrast to the years 1981-1984 and 1988, in 1974 the spring peak was constituted by *Aulacoseira islandica*. The type of dynamism of the pelagic plankton development observed in natural conditions was similar to the model characteristic of lakes with large resources of nutrients, described by Oleksowicz (1988).

Apart from the intensification of movement of the lake water, the setting in motion of the pumped-storage power station in the first place evoked changes in the annual cycle of transformation of chemical composition of the water (Hutorowicz 1993). In consequence, the community of phytoplankton was not affected by a single isolated factor but by a whole complex of them. The most conspicuous (i.e. reproducible) effects of the action of these factors on the plankton community were:

— a distinct quantitative limitation of the development of blue-green algae in summer,

— a gradual shift of the peak of *Aulacoseira* development to summer months with a simultaneous increase in the share of *A. granulata* in relation to *A. islandica*,

— increased importance of monad forms in the spring and summer plankton,

— a shift of the peak of phytoplankton biomass to early spring (1988) or late autumn (1983),

— the obliteration of differences between the pelagic plankton and the studied community of littoral plankton.

In discussing the response of the phytoplankton community in Lake Żarnowiec to the effect of the factor of water movement, a very significant element is the breakdown of biomass in July 1983. The dynamics of development of the community observed in 1982 and 1984 shows that the breakdown cannot be regarded as an effect of consumption of the total nutrient salts during the spring peak. In 1983 this peak was about a half that in the preceding and following years. The hypothesis that in July 1983 the very poor phytoplankton development was brought about feeding zooplankton, should not be excluded.

The cycle of dominance of taxa, formed under the impact of intense water movement, was similar to that observed in slowly flowing lowland rivers (Gocunski 1982, Hübener 1987, Hübener et al. 1989). In these habitats the spring peak was brought about by the mass development of *Stephanodiscus* ssp. and small flagellates. Next, the dominance of *Asterionella formosa*, *Diatoma tenuis*, and *Fragilaria* sp. was observed. In summer there appeared the dominance of blue-green and Protococcales algae (though with a low total biomass), which passed into very strong blooms of diatoms in autumn. The analogy between the two habitats was manifested not only by the similarity of their development during the vegetation season but also by the occurrence of diatoms as the most abundant group both in the lowland rivers and in the phytoplankton of Lake Żarnowiec throughout the years 1983, 1984, and 1988.

6. Polish summary

Fitoplankton Jeziora Żarnowieckiego na tle zmian warunków siedliska wywołanych pracą elektrowni szczytowo-pompowej 2. Dynamika fitoplanktonu

Na podstawie badań prowadzonych na stanowiskach litoralowym i pelagicznym przed, w trakcie i po uruchomieniu elektrowni szczytowo-pompowej scharakteryzowano zmiany dynamiki rozwoju fitoplanktonu w Jeziorze Żarnowieckim.

W stanie naturalnym fitoplankton pelagiczny charakteryzowały stosunkowo małe wielkości biomasy. Średnia roczna biomasa nieznacznie przekraczała 2 mg dm^{-3} (ryc. 1). W sezonie wegetacyjnym występowały dwa szczyty rozwoju. Wiosenny tworzyły okrzemki, najczęściej *Aulacoseira islandica* (O. Müller) Simonsen, *Asterionella formosa* Hassall, *Diatoma tenuis* Agardh, *Stephanodiscus neoastraea* Hakansson et Hickel, *Stephanodiscus* sp. Szczyt letni wywoływały przeważnie sinice z rodzajów *Microcystis* i *Anabaena* lub wymienione już sinice i okrzemki z rodzaju *Fragilaria*. Analogicznie rozwijał się plankton roślinny litoralu, wyróżniając się jednak znacznie większą obfitością, szczególnie zielenic nitkowatych (ryc. 2).

Mieszanie wody w jeziorze, wymuszone działaniem elektrowni szczytowo-pompowej, wyraźnie zakłóciło dynamikę rozwoju fitoplanktonu pelagicznego. Obserwowano:

— występowanie szczytów biomasy fitoplanktonu wczesną wiosną (1988 r.) lub późną jesienią (1983 r.),
— wyraźne ograniczenie rozwoju sinic latem (ryc. 1),
— stopniowe przesunięcie szczytu rozwoju *Aulacoseira* na miesiące letnie, przy jednoczesnym zwiększeniu udziału *A. granulata* w stosunku do *A. islandica*,
— wzrost znaczenia form monadowych w planktonie wiosennym i letnim,
— sporadyczne występownie uwarstwienia pionowego fitoplanktonu w jeziorze,
— zacieranie się różnic pomiędzy planktonem pelagicznym a litoralowym.

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